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FEASIBILITY INVESTIGATION OF EXPANDABLE STRUCTURES MODULE FOR ORBITAL EXPERIMENT - ARTIFICIAL G

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

An expandable structures design concept using a flexible materials composite was investigated and a 30-foot long by 12-1/2-foot diameter prototype fabricated. This work has been directed toward a proposed Apollo Applications Program (AAP) wherein a large expandable structure might be utilized in conjunction with Apollo-type vehicles to conduct partial-gravity experiments. The vehicle would consist of an erectable cylinder 110 feet long and 12-1/2 feet inside diameter which would be launched in the packaged condition and subsequently rendezvoused with a manned Apollo Command Service Module (CSM).

The primary prototype structural material used is a special Dacron tape, 2 inches wide which is longitudinally and circumferentially applied by hand. The cage-type structure confines a bladder comprised of a nylon fabric-film-fabric layer on the inside, a vinyl-foam layer, and an outside nylon-fabric layer. A 1-3/4-inch thick layer of flexible polyurethane foam is applied on the outside of the structure for micrometeoroid protection. Another film-fabric laminate is outside this layer which seals this space to permit squeezing down by evacuating for packaging purposes.

Stainless steel tape in place of Dacron tape is considered.

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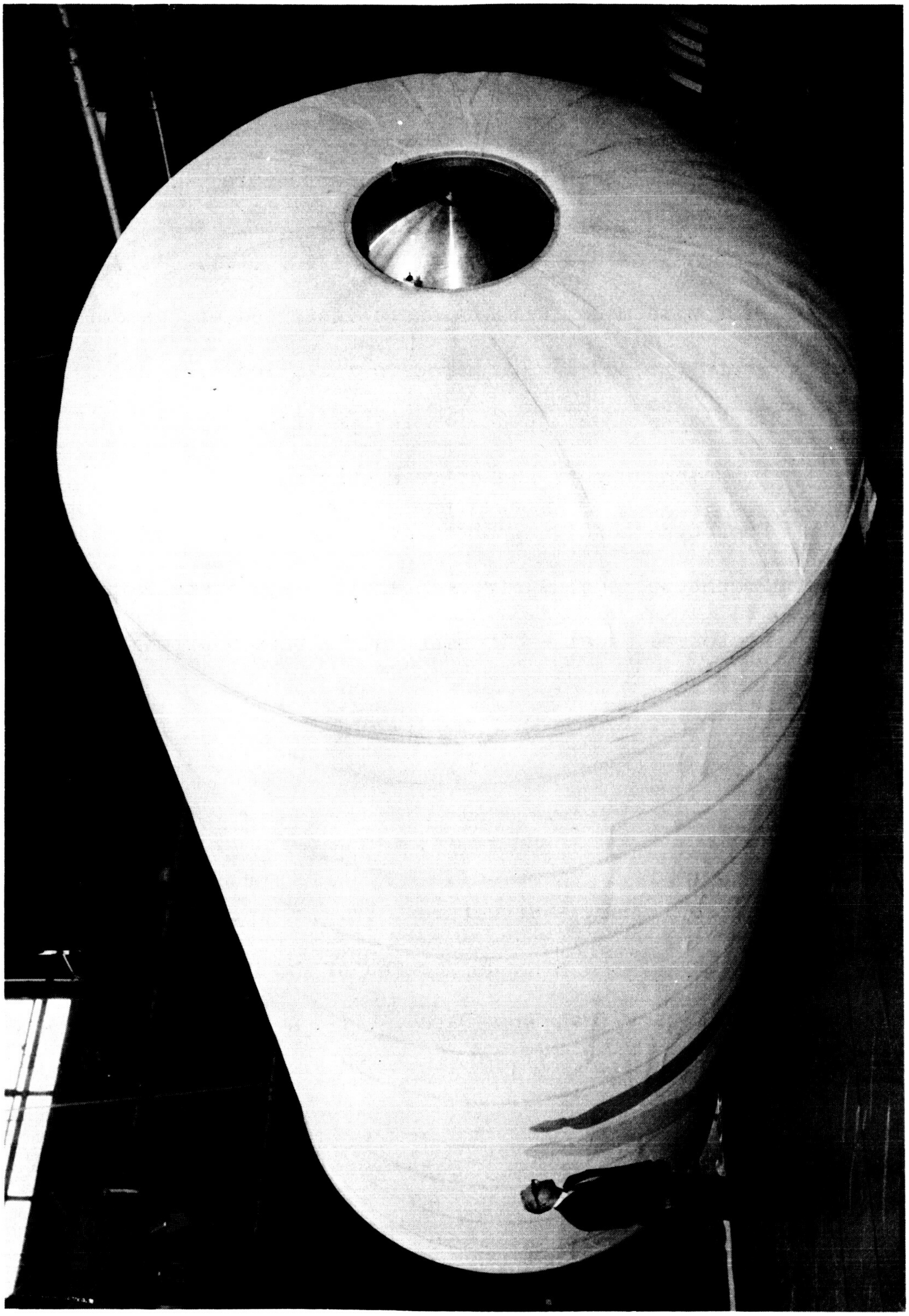

A FEASIBILITY INVESTIGATION OF EXPANDABLE STRUCTURES MODULE FOR ORBITAL EXPERIMENT - ARTIFICIAL G

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SUMMARY

An expandable structures design concept utilizing a flexible materials composite has been investigated. The application was toward a large cylindrical structure to be used for artificial gravity experiments while in earth orbit. The work included design of a full-scale model, design of a prototype (full diameter but with a 30-foot long straight section), fabrication of the prototype, definition of a test program for the prototype, and design of a canister for the prototype test work.

The general shape of the structure is that of a 12-1/2 foot i.d. cylinder. The full-scale unit has a 110-foot long straight section, with convex ends which make the over-all length approximately 117.5 feet. The prototype model is the same except the cylinder portion is only 30 feet long to permit vacuum chamber testing at Langley Research Center (LRC). Rigid metal rings, incorporated at appropriate spacing, provide a uniform fold pattern for packaging. The packaging is accomplished by application of an axial load while twisting at the same time. This technique causes a "necking in" of the flexible material between the rigid rings. A 3-foot diameter door is located at each end. The spacing of the packaging rings does not permit contraction of the flexible structure beyond this dimension. Thus, an astronaut can, if necessary, go through the packaged unit.

The primary structural material used is a special Dacron tape, 2 inches wide which is longitudinally and circumferentially applied by hand, but in a manner simulating a filament wound application. The circumferential tapes are side by side, and the longitudinals are 2 inches apart. The domed ends are tailored to a shape which will result in stress only in the longitudinal direction and need no circumferentials. The resulting cage-type structure is used to confine a bladder assembly which serves as the seal. This assembly is a special laminate comprised of a nylon fabric-film-fabric layer on the inside, a vinyl-foam layer, and an outside nylon-fabric layer.

A 1-3/4-inch thick layer of flexible polyurethane foam is applied on the outside of the structure for micrometeoroid protection. Another film-fabric laminate is outside this layer which seals this space to permit squeezing down by evacuating for packaging purposes. This carries a thermal control coat of paint on the outside.

The above structure is supplemented by miscellaneous hardware items such as external metal rings at the tangent points for canister attachment, end doors and door frames, and several internal rings to facilitate packaging.

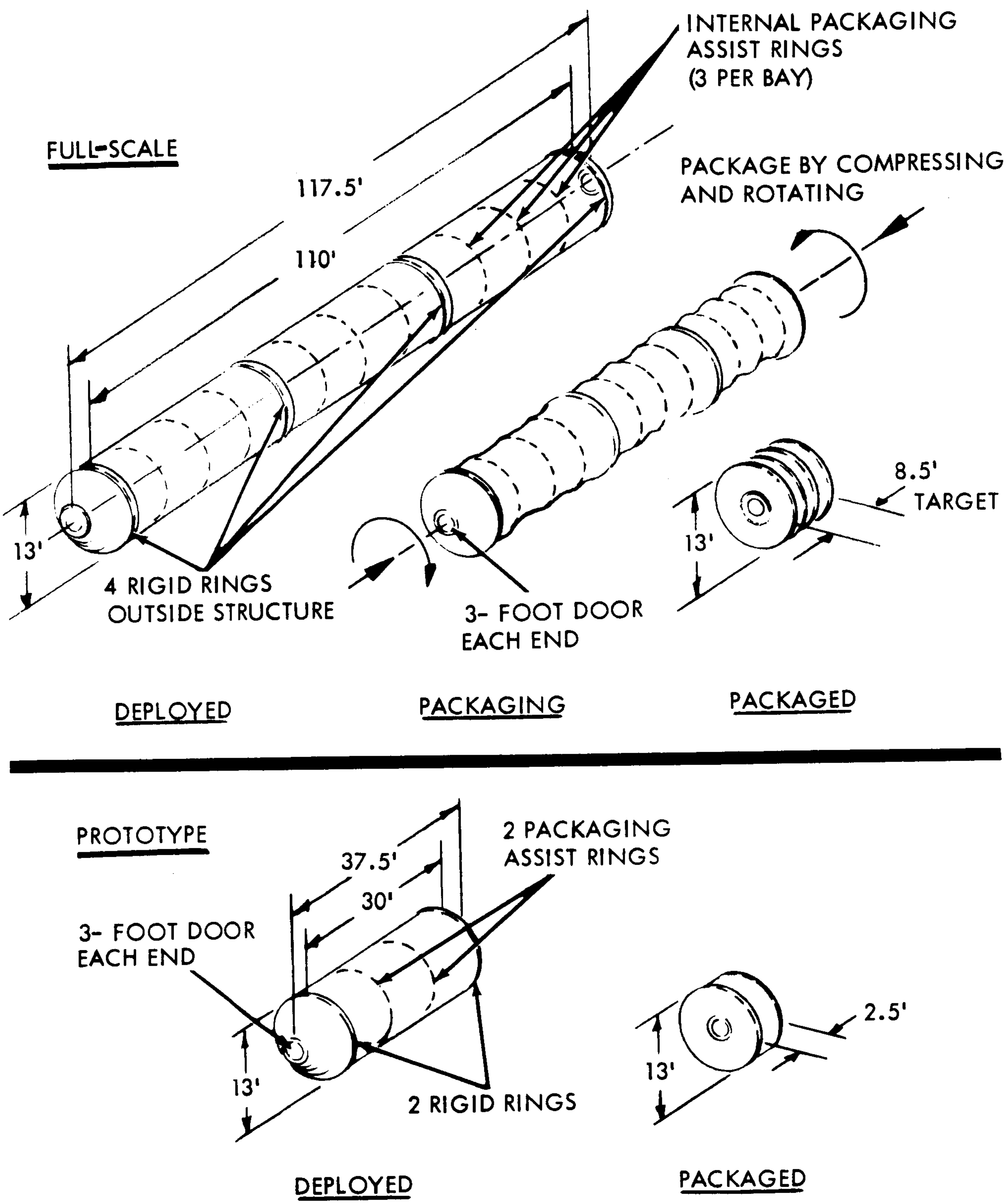


Figure 1. - Expandable structure design concept.

INTRODUCTION

Under NASA-Langley Research Center Contract NAS1-6673, Goodyear Aerospace Corporation has performed the initial tasks toward "A Feasibility Investigation of Expandable Structures Module for Orbital Experiment - Artificial G". This work has been directed toward a proposed Apollo Applications Program (AAP) wherein a large expandable structure might be utilized in conjunction with Apollo-type vehicles to conduct partial gravity experiments. The vehicle would consist of an erectable cylinder 110 feet long and 12-1/2 feet inside diameter which would be launched in the packaged condition and subsequently rendezvoused with a manned Apollo Command Service Module (CSM). After inflation the system would be tumbled to provide various levels of artificial gravity at various locations along the cylinder. The concept would offer opportunity to conduct biochemical operations, and housekeeping experiments at lunar and other gravity levels using very low rates of rotation. The objective of this contract is the development of a concept for the extendable cylinder. The work hereby conducted included the design of such a structure. A prototype test structure was fabricated full scale in diameter and approximately 37-1/2 feet long. A packaging canister for the prototype was designed, and a test program was defined. A preliminary inflation test was carried out to determine leak rate, and conformance of the geometric configuration with the design specification was carried out.

The design concept for this expandable structure is shown in Figure 1. Figure 2 shows the general arrangement of the full-scale unit.

The period of performance for the work reported herein started 20 September 1966, and concluded 19 March 1967.

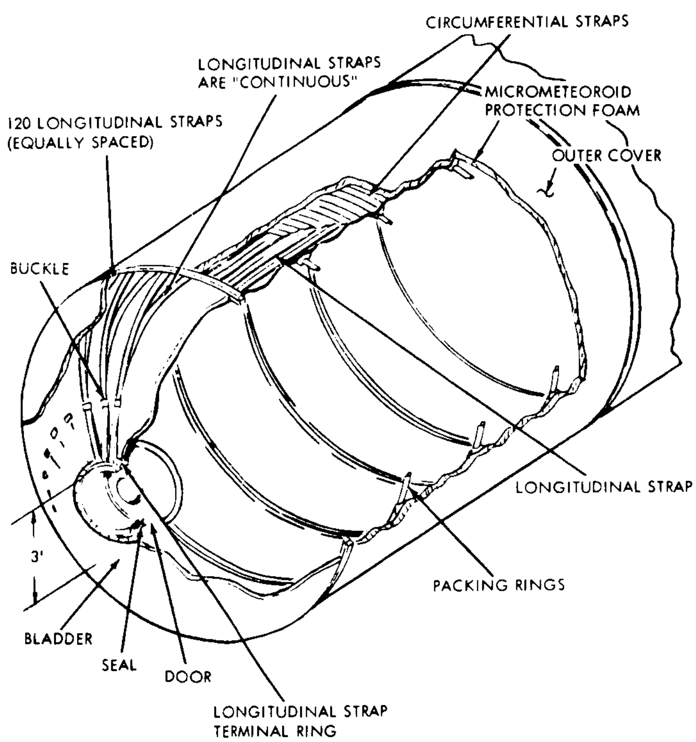


Figure 2. General arrangement - full-scale unit

LIST OF SYMBOLS

Structural Analysis

A,B,O	Location points defined in Figure 10, inch^2
cn	An elliptic function
F.S.	Factor of safety
g	Gravitational acceleration, ft/sec^2
K,E	Complete elliptic integrals of the first and second kinds, respectively
k	Modulus of the elliptic integral
N	Number of structural straps in the meridional direction
N_ϕ, N_θ	Membrane forces in the meridional and circumferential directions, respectively, lbs/inch
p	Inflation pressure, psi
$\bar{R}$	Radius from the axis of revolution to the outermost floor, ft
s	Length along a meridian, ft
S_1	Spacing between meridional straps, inch
T	Tensile force, lbs
u,E(u)	Incomplete elliptic integrals of the first and second kinds, respectively
x,y	Cartesian coordinates, ft
μ	Amplitude of the elliptic integral, degs.
$\rho_\phi \rho_\theta$	Meridional and circumferential radii of curvature, respectively, inch
ϕ	Angle between the normal to the meridian at any point and the axis of rotational symmetry, degs.
ω	Rotational velocity, R.P.M.

Thermal Analysis

C	Solar constant, BTU/hr-ft^2
C_s	Solar heating, BTU/hr-ft^2
E(sin θ)	Complete elliptic integral of the second kind with modulus (sin θ)
F_e	View factor of earth from satellite
I	Earth reradiation heating, BTU/hr-ft^2
K	Altitude parameter
Q	Albedo heating, BTU/hr-ft^2
T_a	Average satellite temperature, deg R
α	Solar absorptance
β	Angle between earth-sun line and orbital plane
ϵ	Emittance
θ	Angle between spin axis and satellite-sun line
σ	Stefan-Boltzmann constant, BTU/hr-ft^2-R^4
τ	Time in sunlight (fractional)
ϕ, ψ	Orientation angles used in derivations

TECHNICAL DISCUSSION OF DESIGN

Objective

The objective of this contract effort was to determine the feasibility of deploying and utilizing a large diameter expandable structure as an integral part of a manned earth orbiting artifical gravity research vehicle by establishing the fabrication techniques, packaging concept, deployment method, and by demonstrating the structural integrity and gas leakage characteristics.

Specific Tasks

Design.

(1) 12-1/2-foot i.d. x 110-foot long expandable cylindrical structure

(2) 12-1/2-foot i.d. x 30 to 40-foot long prototype test module

(3) Canister for prototype testing

Build.

(1) Prototype test module

(2) Miscellaneous composite samples

Design Requirements

Full Scale Model and Prototype.

(1) Operating pressure, 5 psia, Factor of Safety = 3

(2) Permissible leakage, 2% in 24 hr

(3) Micrometeoroid Protection, 0.995 Probability of zero penetration in 14 days at 200 n. mi.

(4) Internal atmosphere, 100% O_2

(5) Thermal control, passive, 70 ± 20° F

(6) Packageable, deployable in ambient and vacuum

(7) Proof pressure, 7.5 psi, 14 days

(8) Deployment by internal gas expansion

(9) Target package length between tangent points, 1/13

(10) Durable, scuff-resistant inner wall

(11) Provisions for attachment at test end of 500 lb. structure to support 500 lb. test equipment

(12) To be rotated 4 RPM (2/3 G)

Canister for Prototype.

(1) For ambient and vacuum chamber use

(2) Simulate full scale packaging requirements

(3) Instrumentation provisions for determining packaging loads

Description of Design Concept

The full scale structure is a straight cylinder, 12-1/2 feet inside diameter, with curved ends. The cylindrical straight section is 110 feet long, with the domed ends adding another 3-3/4 feet each, for a total over-all length of 117.5 feet. The prototype model fabricated under this contract is the same except that the straight section is only 30 feet long (37-1/2 feet over-all). This is shown schematically in Figure 1. Flexible materials are used to permit packaging of this large structure into a small space. However, rigid metal rings are utilized at intervals to provide controlled spacing of the packaging fold locations. Rigid rings are also utilized near the ends where the straight cylindrical section joins the curved ends. These rings also provide points for attachment of the canister.

The primary structural material is a special Dacron tape, 2 inches wide, which is applied by hand but in a manner simulating a filament wound application. The tapes are utilized in both longitudinal and circumferential directions. The circumferential tapes are side by side, and the longitudinals are 2 inches apart. The longitudinals are in effect continuous, running back and forth between 3-foot diameter terminal rings at each end. The circumferentials are also continuous and are applied in a spiral fashion, in the straight cylindrical section only, since the domed ends are tailored to a shape which will result in stress only in the longitudinal direction and need no circumferentials. These tapes are comprised of unidirectional low-twist filaments and therefore provide a relatively high effective modulus, the highest obtainable with Dacron material. The resulting cage-type structure is used to confine a bladder assembly which serves as the seal. This assembly is a special laminate comprised of a nylon fabric-film-fabric layer on the inside, a vinyl foam layer, and an outside nylon fabric layer.

A 1-3/4-inch thick layer of flexible polyurethane foam is applied on the outside of the structure for micrometeoroid protection. Another film-fabric laminate is outside this layer which seals this space to permit squeezing down by evacuating, for packaging purposes. This carries a thermal control coat of paint on the outside.

A three-foot diameter door is included on the centerline at each end. These doors are removable inwardly. The packaging fold pattern is such that a three-foot minimum hole is maintained through the flexible structure when folded. Packaging is accomplished by pressing the ends together while rotating one end relative to the other.

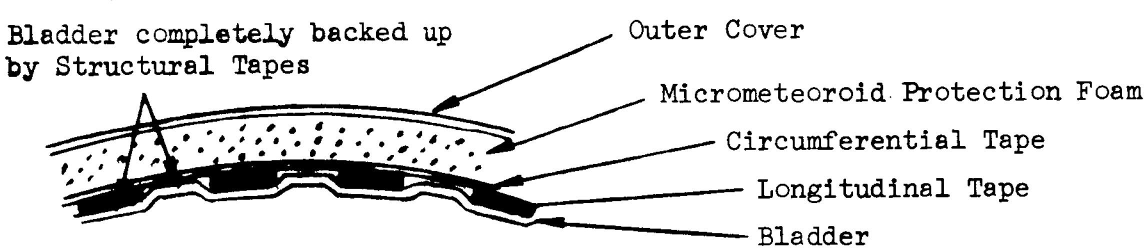
Discussion of Main Structure Elements

Bladder. - The bladder performs the following functions:

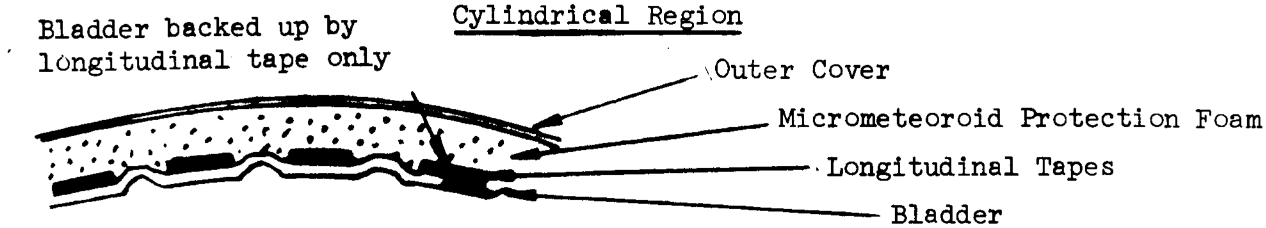
(1) Seal the entire structure from door to door.

(2) Resist internal damage from men working and moving about.

(3) Transmit pressure load to structural tape elements. In the cylindrical section this merely compresses the bladder material. In the curved end regions the structural tapes are approximately 2 inches apart, and the bladder must carry the pressure load to the straps (see the following sketch).



Cylindrical Region



Curved End Region

The seal portion of the bladder composite chosen is a nylon fabric-film-fabric described in the "Materials and Materials Testing" paragraphs. This material has approximately 17 percent ultimate elongation available. It is used in a manner whereby, at the 7.5 psi 14 day proof pressure test condition, its elongation will be approximately 3.85 percent maximum in the cylindrical region.

The foam used in the prototype model is 1/16-inch thick polyvinylchloride (PVC). This layer provides a resilient tacking for the seal layer to minimize susceptibility to punctures. The foam is a closed-cell type so that it also acts as a secondary seal behind the film. As a protection for the bladder during handling and to increase bladder joint reliability, a backing layer of nylon cloth is laminated to the foam.

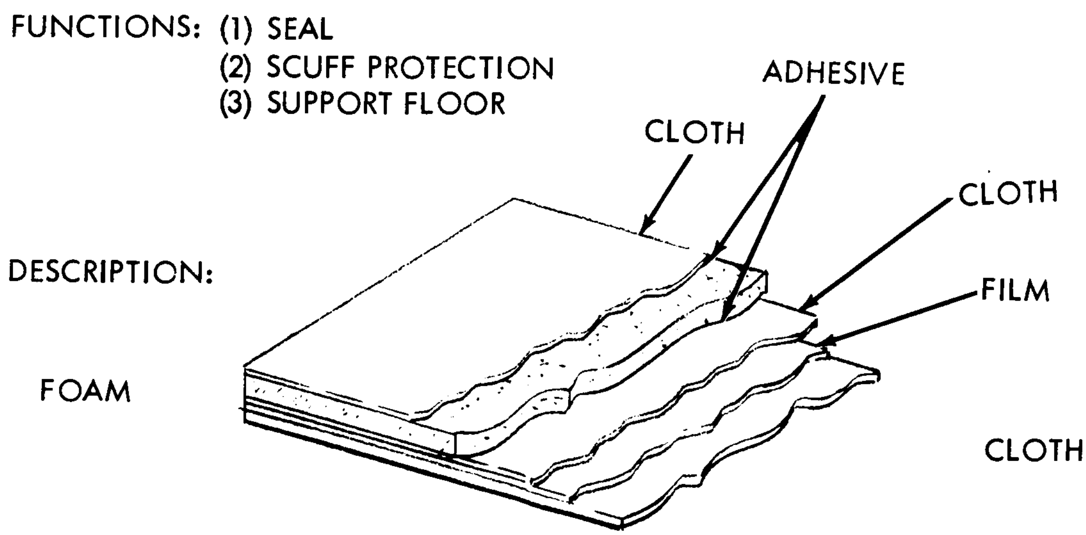
The bladder composite material is laminated in panels approximately 3-1/2 x 16 feet. Therefore, a number of joints are required to tailor the complete bladder assembly. Joints are also required to achieve proper contour in the curved-end regions. Butt-type joints are used, with a film-cloth tape applied to each side. Tightness of the tape joint on the film-cloth side of the bladder is mandatory. Leakage through such a joint is most apt to occur as a result of a slight wrinkle in the tape or the bladder, thereby providing a path under the tape to the joint. For this reason a bead of RTV silicone is inserted in the crack between the adjoining panels and allowed to cure after the first film-cloth tape is applied to the film-cloth side of the bladder. This provides a stop for any potential leakage through wrinkles.

Structural Tape. - High tenacity-type Dacron 52 yarn is utilized for the basic structural material. A very low twist yarn is used to achieve as high effective tensile modulus as possible with this material type. These yarns are made into tape nominally 2 inches wide as shown on Figure 3. The virgin tape so constructed has an ultimate strength of 4390 lbs on a quick-break test. At operating pressure of 5 psia, each tape will be loaded to 750 lbs.

Stainless steel tapes were also considered, and could be substituted. The advantage to be gained would be noticeably lower elongation, and longer useful life under high load conditions. However, a significant weight penalty would result. The weight comparisons are indicated in the "Structural Analysis" paragraphs of this report.

The relative merits of the Dacron vs stainless steel tape materials, from the standpoint of strength and elongation, are portrayed in Figures 4 and 5.

Tape Splices. - The tape is manufactured in lengths of approximately 900 feet, so few splices are required. A steel "buckle" is incorporated at the splice. The strap members to be spliced are inserted through the buckle and bonded to each other with epoxy adhesive. The buckle ensures that good clamping is maintained. Splice joint strengths are 3900 lb minimum.



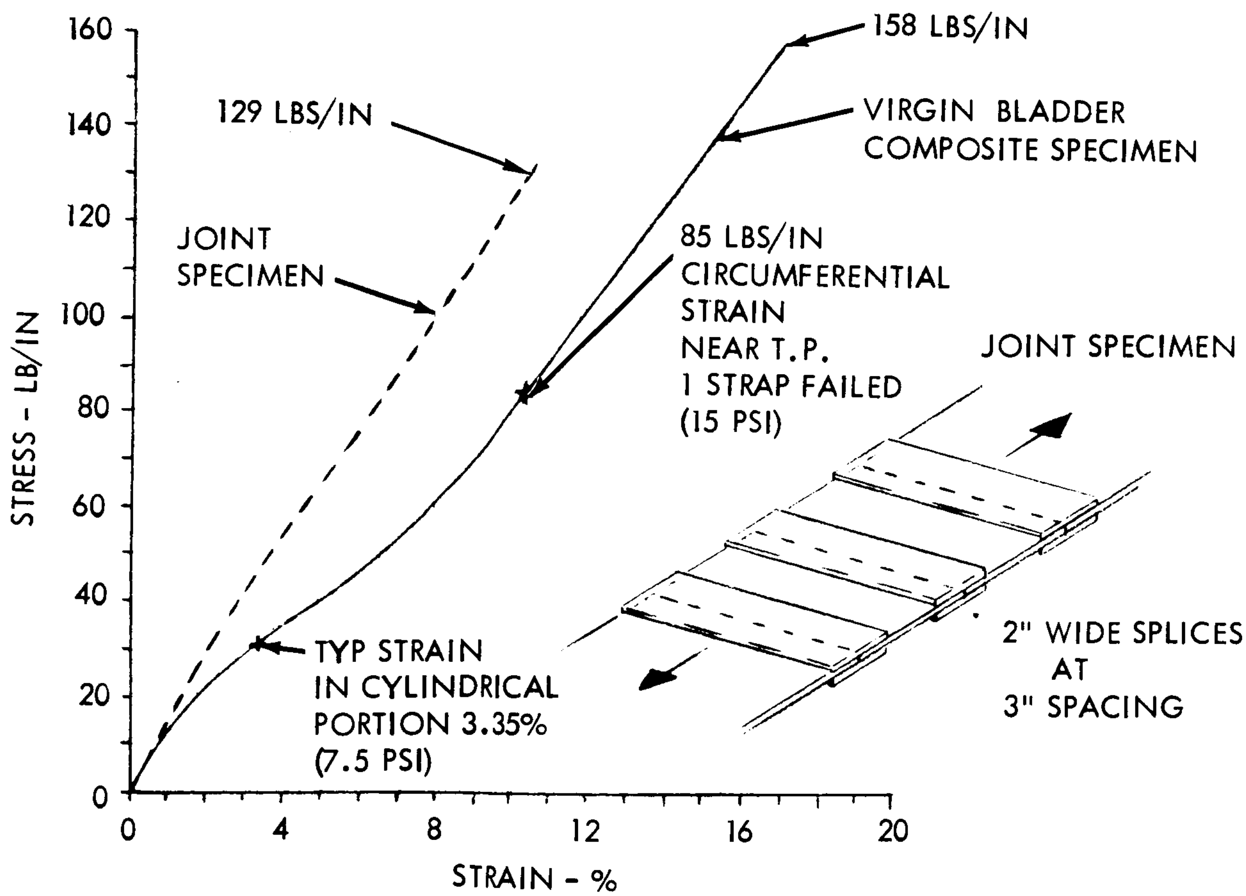


Figure 3. - Bladder stress-strain.

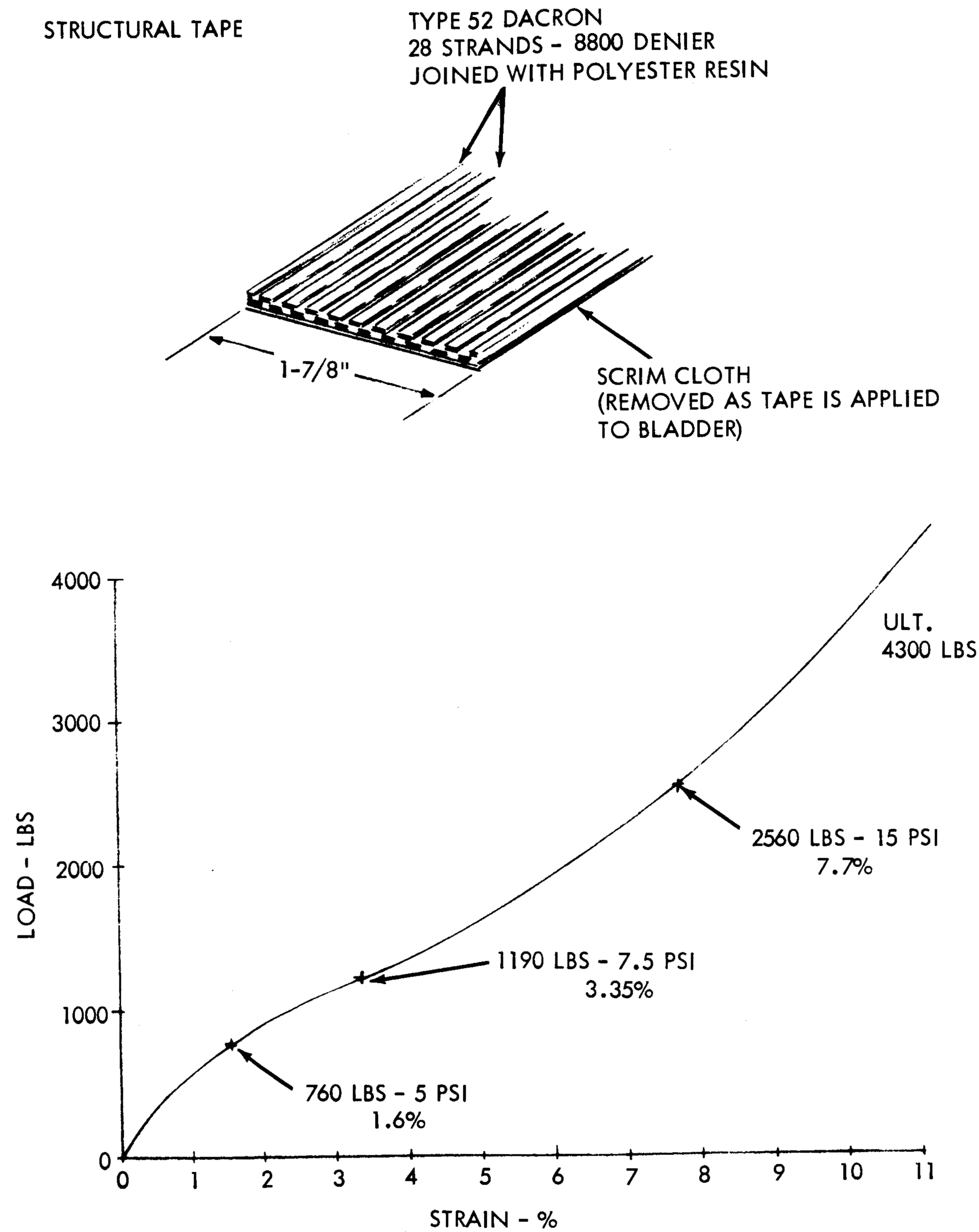


Figure 4. - Load-strain Dacron tape.

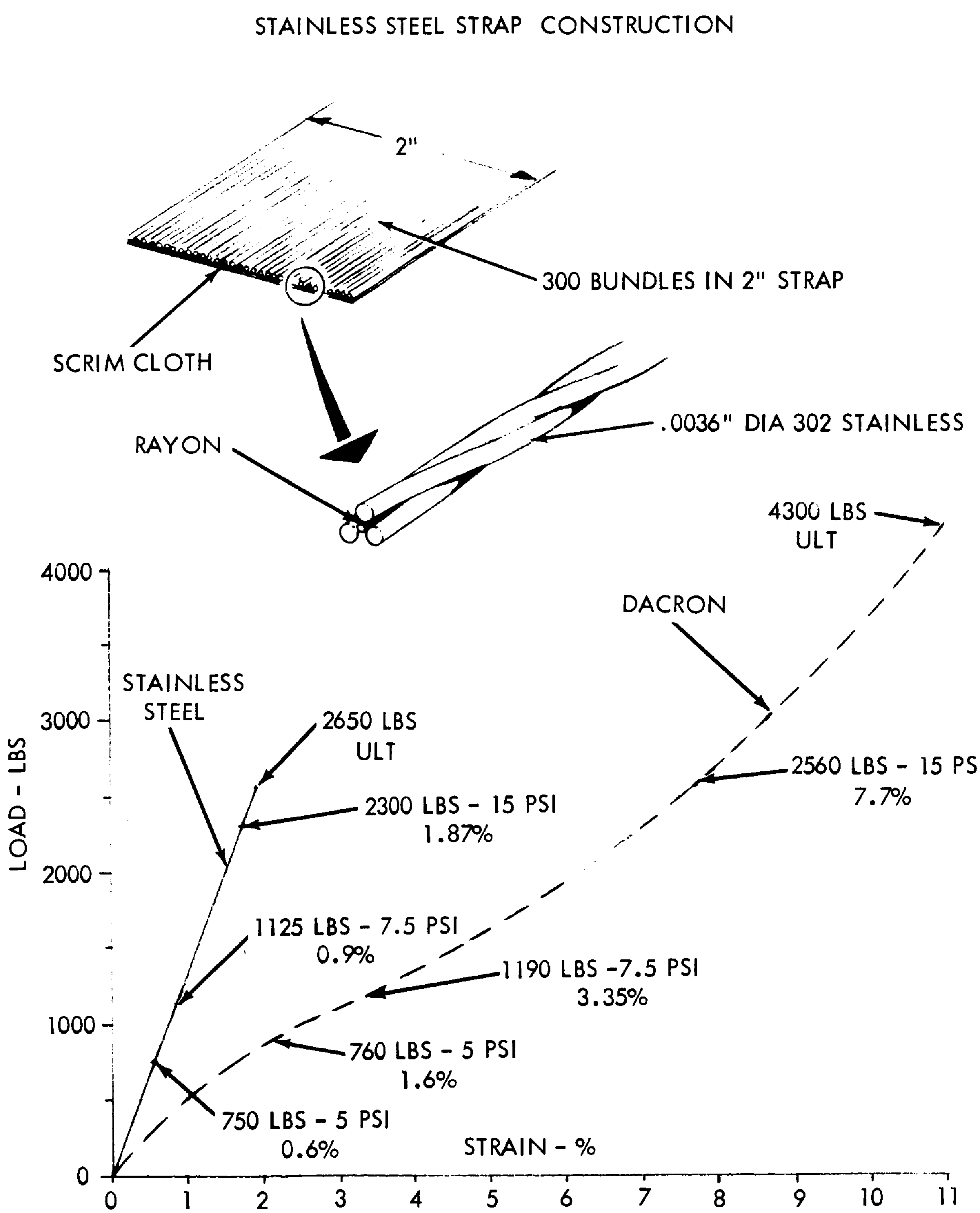


Figure 5. - Load-strain comparison of Dacron and stainless steel straps.

Bladder-Type Subassembly. - The construction of this subassembly involves the application of longitudinal and circumferential tapes to the bladder layer. The same tape construction is utilized in both directions. However, since the load level in the longitudinal direction is 1/2 that in the circumferential direction, the longitudinal tapes are applied 2 inches apart. In the end regions beyond the tangency point where the cylindrical section meets the curve, no circumferential tapes are used. Due to the 2-inch space between tapes, the bladder is unsupported locally in these regions. Adequate elongation is available in the bladder composite to permit it to span the gap between straps. However, a simple modification to the design could completely eliminate this condition. The longitudinal straps could be made the same width but with 1/2 the weight now used, and applied over the entire surface. No unsupported bladder would then exist. The penalty would be a weight increase due to the additional adhesive, and the additional cost of making and installing the additional length of longitudinal tape.

Attachment of tapes to bladder is by RTV silicone applied in a sinewave-type pattern over the entire length of tape.

Strap Terminal Rings. - The longitudinal straps are in effect continuous. A steel ring, 3 feet in diameter, 1-1/8-inch diameter cross section, is inserted at each end. The longitudinal strap goes back-and-forth from ring to ring. Thus, the load from each strap loop is carried by the ring. The rings are made in halves to permit insertion into the strap loops. The ring halves are joined by a threaded fitting. The ring halves have female threads in the ends and are joined by a male fitting with a left hand thread on one end and a right hand thread on the other.

The strap-to-terminal-ring joint arrangement is schematically shown in Figures 2 and 6.

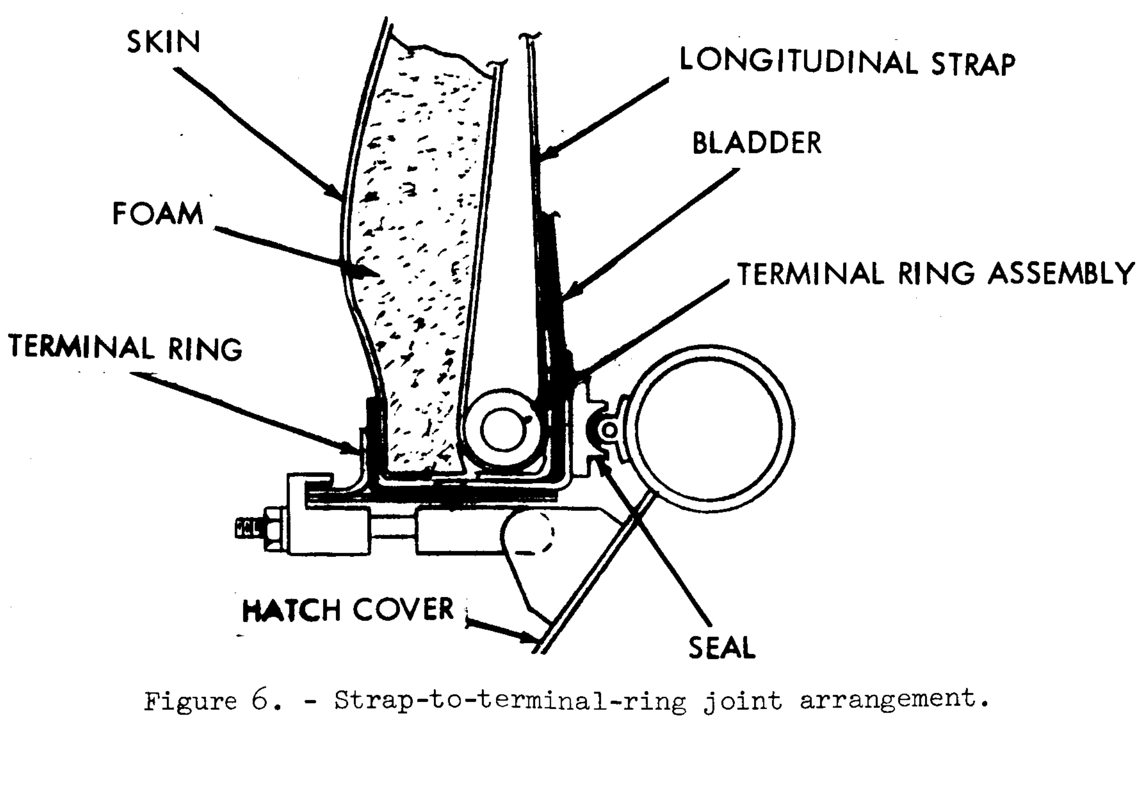


Figure 6. - Strap-to-terminal-ring joint arrangement.

Tangent Rings. - Figures 2 and 7 depict the arrangement in the region where the contoured ends meet the straight cylindrical section. Three-inch square cross-section aluminum rings are attached to the outside of the structure in these regions. These rings provide hard attach points for the canister and also control the primary fold locations in the end regions, and act as manifolds for the evaluation of the wall of the structure prior to packaging. Attachment of these rings to the soft structure is made prior to application of the circumferential tapes. This is accomplished by bonding short lengths of the Dacron tape material to the longitudinal straps and the rings (See Figure 7).

A 3-inch wide aluminum channel ring is inserted on the inside of the bladder at these tangent locations. This ring is split, and a turnbuckle arrangement used to provide clamping pressure against the inside of the bladder. RTV silicone is used as a bonding agent. Thus, adequate attachment is made without requiring any holes in the bladder. The function of these rings is to provide structure to which a floor could be attached when implemented for an artificial gravity experiment. These channels also provide means of attaching a temporary internal spider to the cylinder. This spider is utilized in the manufacturing operation of turning for application of the circumferential tapes.

Bladder Terminal Rings. - Since a 3-foot diameter door is incorporated into each end of the structure, a framing of this door is required. This provides a place to terminate the bladder, and to mount the door seals (see Figure 6). The arrangement used provides two aluminum angles with the bladder end sandwiched between. Sealing and bonding of this joint is accomplished with RTV silicone.

The inner face of this frame is a flat surface to which one element of the door seal is attached.

This door frame also provides an external flange for attachment and sealing of the outer cover.

Doors. - A 3-foot diameter aluminum spun door with a spherical radius is located at each end. One of these doors has an 8-inch diameter acrylic window in the center and ports for pressure line attachment and instrumentation wiring insertions. An annular tube frame is attached by welding. One-half of the rubber door seal is attached to this tube.

Loose fitting latches are attached to these doors for the test article. These provide means of holding the door in position snugly until the internal pressure exerts enough force on the door to effectively mate the seals.

Packaging Rings. - Packaging is to be achieved by compressing the unit endwise, while rotating one end on its axis in relation to the other end. Twisting one end relative to the other causes a "necking-down" between the rigid tangent rings. By incorporation of additional stiff rings at appropriate length-wise locations, the contraction inwardly can be limited to retain an opening from

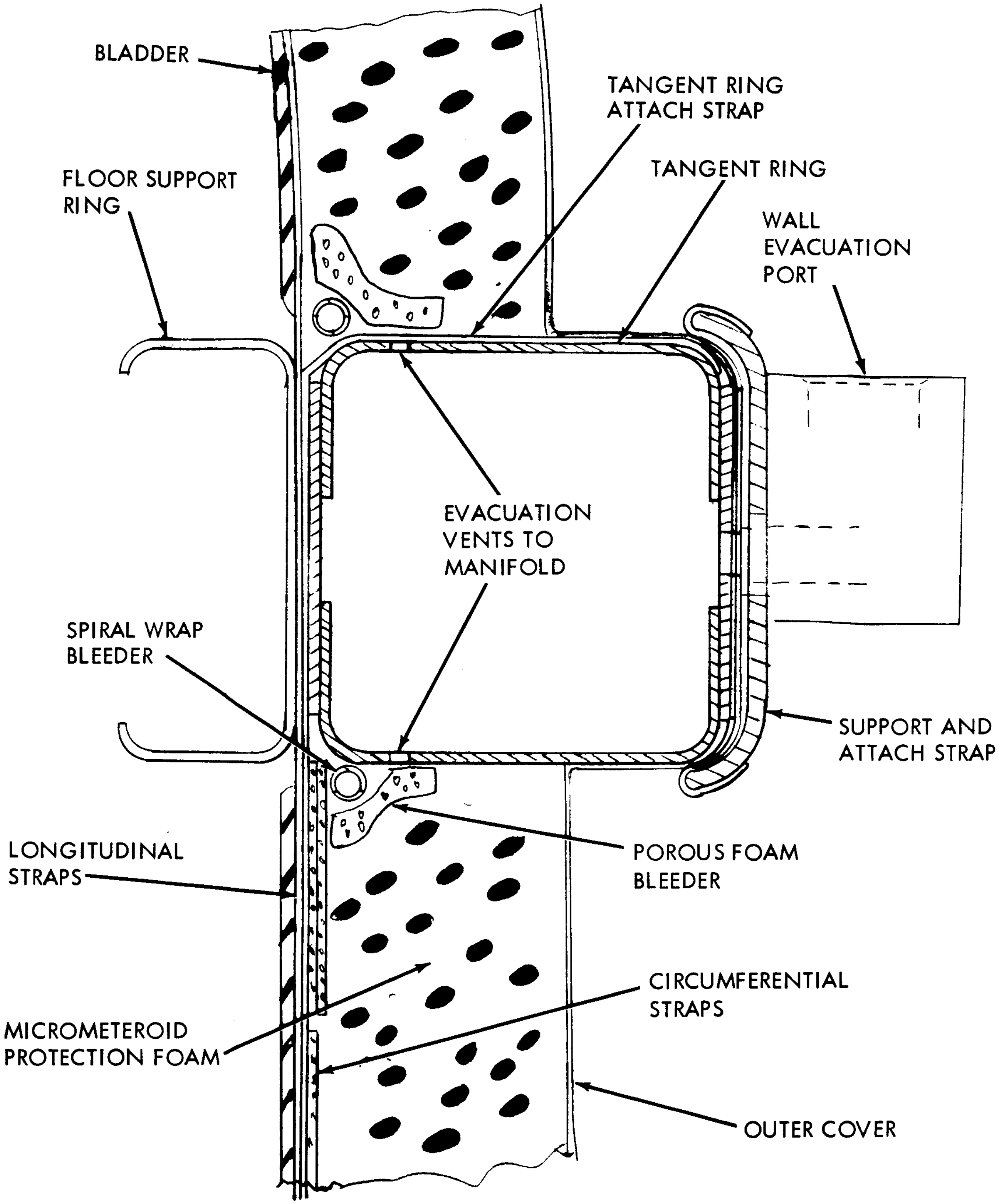


Figure 7. - Tangent ring joint

one end to the other while in the packaged condition. For the test article, two such rings are used. Thus, the 30-foot length between tangent rings is divided into three 10-foot increments for packaging.

These rings are of 3-inch diameter aluminum tubing. Attachment to the bladder is complicated somewhat by the fact that the bladder will elongate when pressurized. Therefore, if rigid attachment were made between the rings and the bladder it would result in a restriction of the bladder elongation, and would put undesirable local loads into the bladder. This problem was overcome by use of flexible foam for this attachment. The outside diameter of the rings is slightly less than the inside diameter of the bladder with no internal pressure. A foam annular ring of rectangular cross-section is laced between the ring and the bladder. The rings are attached to the foam by straps. Under no-load condition the foam is compressed. As internal pressure is applied, the structure expands, and the foam expands to make up the difference in diameter between the ring and the structure. The foam is incapable of transmitting severe local loads from structure to ring, thereby providing protection for the bladder.

Weight

The calculated weights of the full-scale structure and the prototype model are tabulated in Table I. These weights are based on the engineering designs now complete and the amounts of adhesives utilized in fabrication of the prototype model.

An alternate design utilizing longitudinal strap material 1/2 as heavy as shown in the designs, but completely covering the bladder, would increase the total adhesive requirements. A comparable prototype weight would then be 1725 lb compared to 1622 lb for the existing model. Comparable full-scale unit weights would be 5511 lb for Dacron strap type and 6196 lb using stainless steel for strap material.

The weight of the adhesive system shown for attachment of straps is maximum. and measurable reduction in this weight should be attainable with optimum design.

The material composite used for the prototype model weighs 0.815 lb/sq ft. The comparable structure if stainless steel were used would weigh 0.955 lb/sq ft. These numbers would be increased to 0.875 and 1.015 respectively if lighter longitudinal tape were used over the entire area.

TABLE I. - WEIGHT SUMMARY - STRUCTURE

Structure	Weight - lb		
	Prototype	Full Scale	
		Dacron Straps	Stainless Straps
Hard Structure			
External Tangent Rings (2)	112	(4) 224	224
Internal Tangent Rings (2)	40	(4) 80	80
Strap Terminal Rings	50	50	50
Door Frames	9	9	9
Doors	20	20	20
Packaging Rings (2)	56	(9) 253	253
Attachment Straps (2)	48	(2) 48	48
Subtotals (A)	335	684	684
Flexible Structure			
Bladder	168	830	830
Longitudinal Tapes	140	370	625
Circumferential Tapes	170	620	1050
Micrometeoroid Foam	275	835	835
Outer Cover	100	303	303
Interlayer and Seam Adhesive	434	1449	1449
Subtotals (B)	1287	4407	5092
Total - (A) + (B)	1622	5091	5776

Structural Analysis

The structural analysis, summarized herein, was conducted in support of the design of both the full size expandable structure and the prototype test structure. The detailed coverage is presented in Reference 1. Calculated margins of safety of the critical structural components are given herein along with the corresponding factors of safety, loading conditions and failure modes. A discussion of the unit, isotensoid (zero circumferential stress) end closure is also given.

There are two differences between the flight article and its prototype:

(1) The lengths of the cylindrical portions of the flight article and the prototype are 110 feet and 30 feet, respectively.

(2) An 8-inch diameter window is used in one of the access hatches of the prototype but is omitted in the design of the flight article.

The structural straps of the flight article and the prototype are composed of Dacron yarns. Straps of stainless steel yarns could be used as an alternate construction. If steel wires were used, the primary differences would be less longitudinal and circumferential elongations and less tension in the tangency rings as compared to the Dacron yarn construction. Margins of safety of an alternate steel wire construction are included in Table II.

The basic structural components are:

(1) <u>Cylinder</u> - Composed of nominal 2-inch wide straps with the circumferential windings being contiguous, whereas the 120 longitudinal 2-inch wide straps are spaced about 4 inches between centers to yield the desired equal stress condition.

(2) <u>Isotensoid Zero Hoops End Closures</u> - Designed to have the proper shape under the operating internal pressure so that only meridional stresses are present which are carried by continuing the 120 longitudinal straps as meridional straps.

(3) <u>Terminal Rings</u> - The meridian straps of the end closures terminate at steel tension rings of nominal 3-foot diameter. These rings also support the access hatches.

(4) <u>Access Hatches</u> - The 3-foot diameter aluminum circular hatches are thin spherical shells with supporting edge rings.

(5) <u>Tangency Rings</u> - These are built-up aluminum box section rings that are externally located at the tangent stations of the cylinder and the end closure junction. They provide for the attachment of the packaging canister.

(6) <u>Internal Packaging Rings</u> - These are placed inside the cylinder at regular intervals in order to control the collapsing of the cylinder wall during packaging.

TABLE II. - SUMMARY OF THE MINIMUM MARGINS OF SAFETY

Structural Component	Minimum Margin of Safety	Factor of Safety	Loading Condition	Failure Mode	Comments
Meridional & Circumferential Straps					
Steel Yarns	+0.15	3.0	1-e Ultimate Internal Pressure	Tension	
Dacron Yarns	+0.71	3.0	1-e Ultimate Internal Pressure	Tension	
Strap Connections					
Steel Yarns	-0.0	3.0 + 1.2	1-e Ultimate Internal Pressure	Tension	
Dacron Yarns	+0.19	3.0 + 1.2	1-e Ultimate Internal Pressure	Tension	
Bladder	+0.88	3.0	1-e Ultimate Internal Pressure	Tension	
Terminal Ring	High	3.0	1-e Ultimate Internal Pressure	Tension	
Splices	+0.19	3.0 + 1.2	1-e Ultimate Internal Pressure	Tension	
Internal Packaging Rings	+0.05	1.5	2 External Pressure	In Plane Buckling	
	+1.29	1.5	3 1-G Handling Loads	Compressive Yielding	
Tangency Rings (Dacron Yarns)	+0.28	3.0	1-e Ultimate Internal Pressure	Tension	The steel yarn construction is not critical because of the lesser stretch.
Splices	+0.09	3.0 + 1.2	1-e Ultimate Internal Pressure	Shear in the rivets of the sector splices	
Internal Floor Support Rings	+1.0	1.5	Ring Compression Load = 225 lbs	Column Buckling of Turnbuckle	Since the initial ring radius will be changed to equal the cylinder radius, this load will probably not be obtained.
Access Hatches					
Dome	High	3.0	1-e Ultimate Internal Pressure	Tension	
Edge Ring	High	3.0	1-e Ultimate Internal Pressure	In Plane Buckling	
Window	+0.21		1-b Proof Pressure	Flexure	
Window Reinforcement Ring	+0.97	3.0	1-e Ultimate Internal Pressure	Combined Tension and Buckling	
Spot Welds	+1.73	3.0	1-e Ultimate Internal Pressure	Shear	

(7) Internal Floor Support Rings - These rings are placed inside the cylinder in the same plane as the tangency rings. They will support the floor required for the artificial gravity experiment.

In addition to the connections required for the above structural components, there is an internal foam-fabric pressure bladder and an external micrometeoroid protection foam. The construction is schematically shown in Figure 8 below:

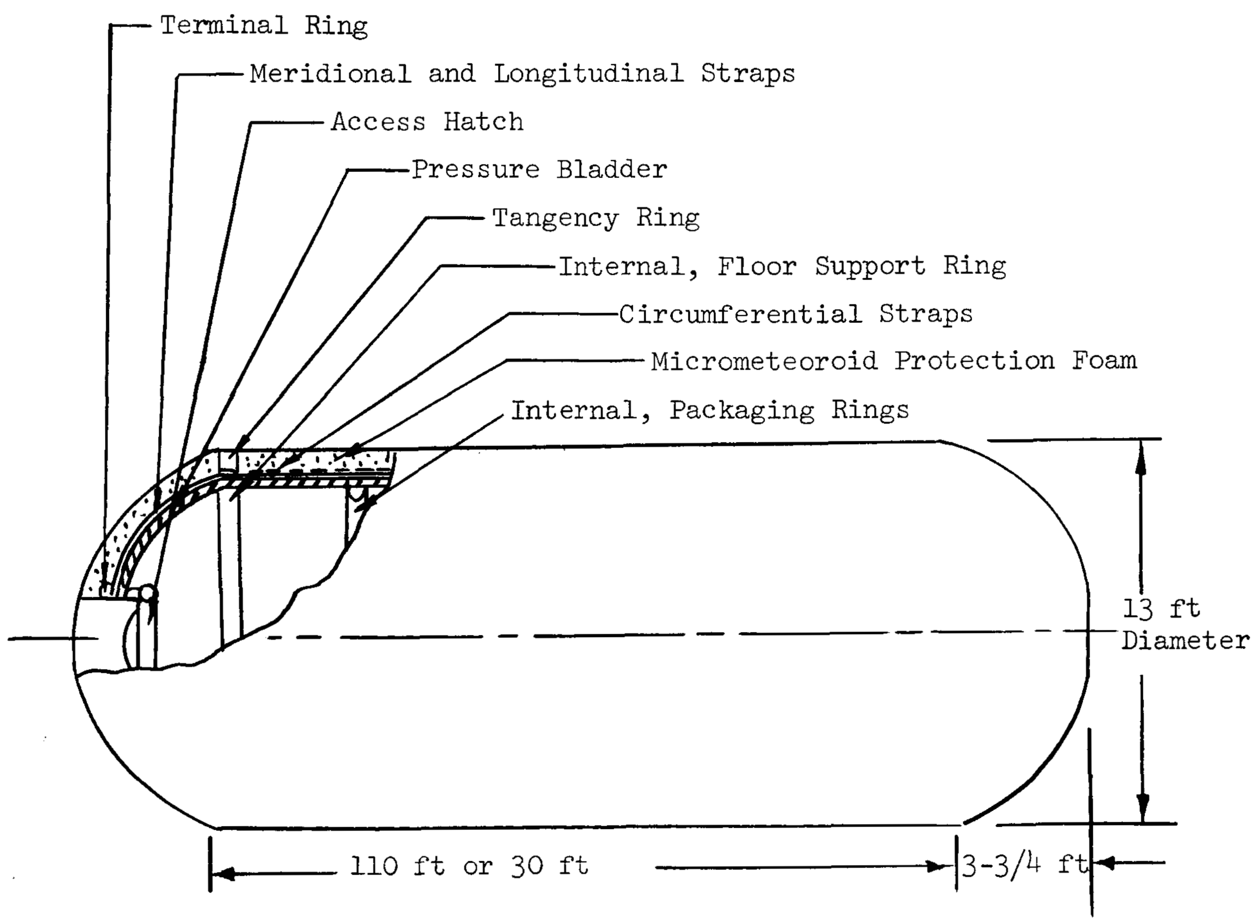


Figure 8. - Configuration

The structure has been analyzed for the following loads:

(1) Internal Pressure

(a) Operating (limit) pressure = 5 psig.

(b) Proof pressure = 7.5 psig. This pressure will be maintained for 14 days to make a leakage test

(c) Ultimate pressure = 15 psig.

(d) Fabrication Pressure = 0.1 psig.

(2) External Pressure
It may be necessary to apply a small external pressure to assist in the packaging of the cylinder. This is taken as 0.25 psig.

(3) 1-G loads during handling and fabrication.

(4) Centrifugal forces due to the mass of a 1000 lb. floor load rotating at 4 rpm about an axis located 120 feet from the floor location, and perpendicular to axis of the cylinder.

Of the above loads, condition 4 causes negligible stresses as compared to those due to condition 1-c as shown below.

The force in one of the 120 longitudinal straps due to the ultimate internal pressure is 2510 lbs. as given by equation (16). The corresponding force due to condition 4 is only 16.4 lbs, i.e.

$$T_{ug} = (F.S.) \frac{\bar{R}\,\omega^2\,W_f}{120\,g} = (3)\,\frac{(120)\left[(4)\left(\frac{2\pi}{60}\right)\right]^2 (1000)}{(120)(32.2)} = 16.4 \text{ lbs,}$$

All structural components are considered to be subjected to room temperature conditions at all times (70° ± 20° F.).

Although, the ultimate factor of safety of 3 is specified to be applied to all structural components, an additional fitting factor of 1.2 is used for those connections considered to be critical. A factor of safety of 1.5 is applied to the limit loads for analysis of those compoments that are subjected to elastic buckling. The results of the structural analysis are summarized as the minimum margins of safety in Table II.

The inflated end closure, or dome, is designed as an isotensoid surface of revolution. These surfaces are used extensively in the filament winding of pressure vessels, rocket cases, etc. High strength to weight ratios result since a nearly uniform factor of safety is achieved throughout the body due to constant stresses in the filaments. This shape was first treated mathematically by G. I. Taylor (Reference 2) in the early twenties for the purpose of describing the shape of parachutes. The parametric equations of the curve involve elliptic functions and are presented in Figure 10 along with a non-dimensional plot of the profile.

The principal membrane forces are considered along with the uniform internal pressure that act on a surface element of the dome located at point A of Figure 9 below.

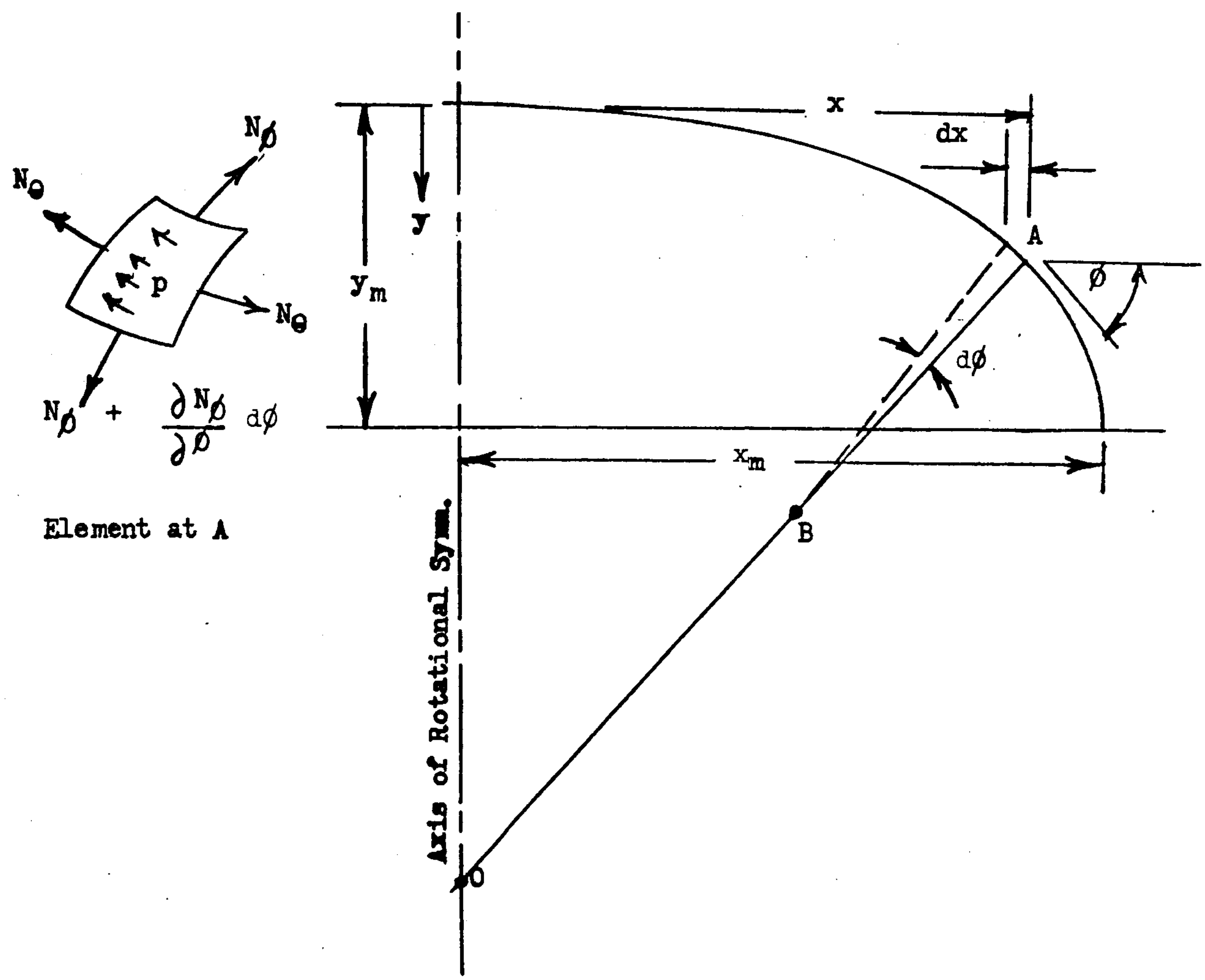


Figure 9. - Geometry and surface element of the Taylor's Dome.

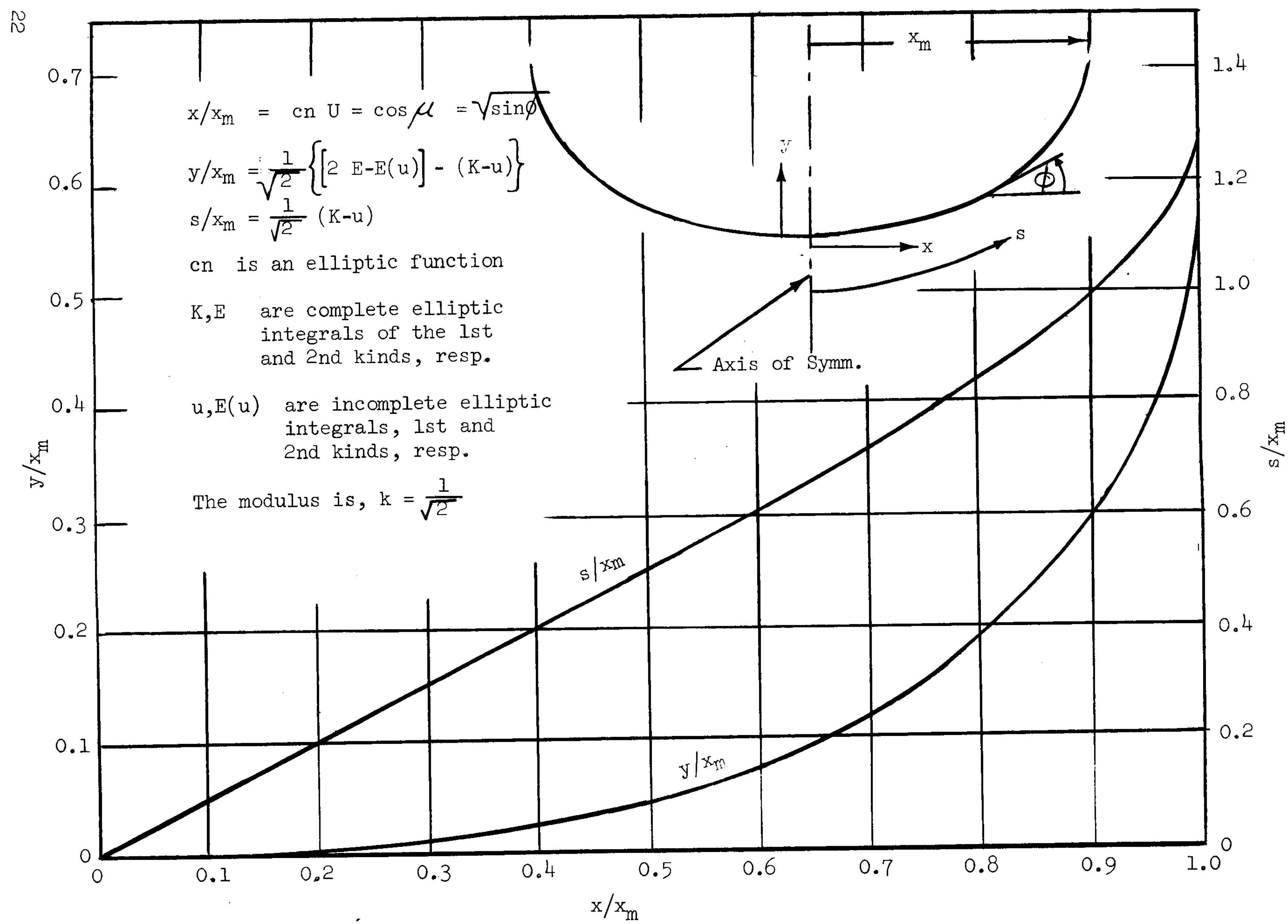


Figure 10. Dimensionless coordinates and meridian length of the Taylor's Curve

In Figure 9, the lengths BA and OA represent the meridian and circumferential radii of curvature (ρ_ϕ and ρ_θ), respectively. Similarly, N_ϕ and N_θ are the corresponding, principal meridian and circumferential membrane forces due to the uniform, internal pressure, p.

From the geometry of Figure 9

$$OA = \rho_\theta = x \csc \phi \tag{1}$$

$$BA = \rho_\phi = \frac{dx}{d\phi} \sec \phi \tag{2}$$

However, the equation of the Taylor's curve (Reference Figure 9) is,

$$x = x_m \sqrt{\sin \phi} \tag{3}$$

Differentiation of equation (3) gives

$$\frac{dx}{d\phi} = \frac{x_m \cos\phi}{2 \sin \phi} \tag{4}$$

Substituting equations (3) and (4) into equations (1) and (2), respectively gives

$$\rho_\theta = \frac{x_m}{\sqrt{\sin \phi}} \tag{5}$$

$$\rho_\phi = \frac{x_m}{2\sqrt{\sin \phi}} \tag{6}$$

Consider the equilibrium of the portion of the dome above a parallel circle defined by the angle ϕ of Figure 10. The resultant pressure load ($p\pi x^2$) is reacted by the distributed meridian membrane forces. The equation of equilibrium is then,

$$2\pi x N_\phi \sin \phi = p\pi x^2 \tag{7}$$

and

$$N_\phi = \frac{px}{2 \sin \phi} \tag{8}$$

A second equilibrium equation may be derived by considering the forces acting normal to a surface element. This is the well known membrane equation.

$$\frac{N_\phi}{\rho_\phi} + \frac{N_\theta}{\rho_\theta} = p \qquad (9)$$

or

$$N_\theta = \left(p - \frac{N_\phi}{\rho_\phi}\right) \rho_\theta \qquad (10)$$

Dividing equation (8) by equation (6) gives

$$\frac{N_\phi}{\rho_\phi} = \left(\frac{px}{2 \sin \phi}\right) \left(\frac{2\sqrt{\sin \phi}}{x_m}\right) = \frac{px}{x_m \sqrt{\sin \phi}} \qquad (11)$$

Substituting equation (3) into equation (11) gives

$$\frac{N_\phi}{\rho_\phi} = p \frac{x_m \sqrt{\sin \phi}}{x_m \sqrt{\sin \phi}} = p \qquad (12)$$

Therefore, substitution of equation (12) into equation (10) shows the circumferential stress is zero throughout the dome, i,e.,

$$N_\theta = (p - p) \rho_\theta = 0 \qquad (13)$$

A second characteristic of a Taylor's dome, that is constructed of a finite number of meridian cords, is that the tension in each cord is constant along the cord. For N cords, the circumferential spacing between them is

$$s_1 = \frac{2\pi x}{N} \qquad (14)$$

The tensile load in a cord is simply the meridian membrane force, given by equation (8), multiplied by the cord spacing, i.e.,

$$T = N_{\phi} s_1 = \left(\frac{px}{2 \sin \phi}\right)\left(\frac{2\pi x}{N}\right) = \frac{p\pi x^2}{N \sin \phi} \tag{15}$$

Squaring equation (3) and substituting the result into equation (15) shows the cord tension is constant and equal to,

$$T = \frac{p\pi x_m^2}{N} \tag{16}$$

A dome having an equatorial diameter of 12.5 feet when inflated to an operation (limit load) gage pressure of 5 psi is desired. A centrally located, access hatch is also specified. The meridian elements are therefore terminated at a central ring having a diameter of three feet. Letting x_r be the radius of this ring, the location on the dome is then given by the equations of Figure 10 as,

$$\cos \mu_r = \sqrt{\sin \phi_r} = \frac{x_r}{x_m} = \frac{1.5}{6.25} = 0.24$$

$$\mu_r = \cos^{-1} 0.24 = 76° \, 6.8'$$

$$\phi_r = \sin^{-1} (0.24)^2 = 3° \, 18.1'$$

The length along the generating meridian as well as its Cartesian coordinates is also desired for fabrication purposes. The infinitesimal length is

$$ds = \rho_{\phi} \, d\phi \tag{17}$$

Substituting equation (2) into equation (17) gives

$$ds = d_x \sec \phi \tag{18}$$

or

$$ds = \frac{dx}{\sqrt{1 - \sin^2 \phi}} \tag{19}$$

But from equation (3)

$$\sin^2 \phi = \left(\frac{x}{x_m}\right)^4 \tag{20}$$

Substituting equation (20) into equation (19) gives

$$ds = \frac{dx}{\sqrt{1 - \left(\frac{x}{xm}\right)^4}} \tag{21}$$

Now consider the elliptic functions:

$$\mathrm{cn}\, u = \frac{x}{x_m} \tag{22}$$

$$\mathrm{sn}^2 u = 1 - \mathrm{cn}^2 u = 1 - \left(\frac{x}{x_m}\right)^2 \tag{23}$$

$$\mathrm{dn}^2 u = 1 - k^2 \mathrm{sn}^2 u = 1 - k^2\left(1 - \frac{x^2}{x_m^{\ 2}}\right) \tag{24}$$

Let the modulus, k have the value,

$$k = \frac{1}{\sqrt{2}} \tag{25}$$

Substituting equation (25) into equation (24) gives

$$\mathrm{dn}^2 u = \frac{1}{2}\left(1 + \frac{x^2}{x_m^{\ 2}}\right) \tag{26}$$

Multiplying equations (23) and (26) gives,

$$\mathrm{sn}^2 u\, \mathrm{dn}^2 u = \frac{1}{2}\left(1 - \frac{x^4}{x_m^{\ 4}}\right) \tag{27}$$

or, taking the square root of equation (27) gives,

$$\sqrt{1 - (\frac{x}{x_m})^4} = \sqrt{2}\ \mathrm{sn}\ u\ \mathrm{dn}\ u \tag{28}$$

Next, differentiating equation (22) gives,

$$dx = -x_m\ \mathrm{sn}\ u\ \mathrm{dn}\ u\ du \tag{29}$$

Finally, substituting equations (28) and (29) into equation (21) gives,

$$ds = -\frac{x_m}{\sqrt{2}}\ du \tag{30}$$

The desired meridian length is given by integrating equation (30). Here, the lower limit of integration is the complete elliptic integral of the first kind since when $x = 0$, $\mathrm{cn}\ u = 0$ [by equation (22)]. Therefore,

$$s = -\frac{x_m}{\sqrt{2}} \int_K^u du = \frac{x_m}{\sqrt{2}} (K - u) \tag{31}$$

or, from the tables of elliptical integrals for the modulus,

$$k = \frac{1}{\sqrt{2}}, \quad K = 1.8541 \text{ and,}$$

$$s = \frac{x_m}{\sqrt{2}} (1.8541 - u) \tag{32}$$

Here, of course, u denotes the incomplete elliptical integral of the first kind,

The meridional length was determined for values of u using equation (32). The corresponding values of x were calculated by equation (22) and the meridional length curve of Figure 9 was then plotted.

Materials and Materials Testing

A detailed "Materials and Materials Testing" report (GER-13161, Reference 3) has been published in compliance to Clause 41 of this contract.

Micrometeoroid Protection

A theoretical study was conducted to determine the amount of flexible foam micrometeoroid protection required to satisfy the specifications of 0.995 probability of zero penetration at 200 n. mi. for 14 days. The environment criteria was that defined by Reference 4. Appropriate calculations using these parameters showed that it would be necessary to stop particles of 3.3 mg or less. In past programs, it has been found that 1.75 inches of the elastic recovery material planned for this structure is adequate to stop all stony-type particles having a mass of 3.5 mg or less. This is documented in Reference 5. The integrity of the composite relative to micrometeoroid protection is significantly related to the bumper wall used. Specimens of the composite material herewith used were furnished to LRC under this contract for subsequent micrometeoroid testing. These tests should determine whether the present outer cover is adequate, or should be altered to improve its capability to break up the particles.

Thermal Analysis

A tumbling cylinder in a 200 n. mi. orbit ($K \cong 0.95$), with an orbital inclination β with respect to the earth-sun line, and an angle θ between the spin axis and the cylinder-sun line is considered.

For a low orbit

$$F_e \cong 0.5\left(1 - \sqrt{1 - K^2}\right) = 0.344 \tag{33}$$

Therefore, earth heating is

$$I = 0.16\, C\, F_e = 24.4 \ \mathrm{BTU/hr\text{-}ft^2} \tag{34}$$

Albedo heating averaged over the orbit is

$$Q \cong 0.36\ C\ F_e \cos\beta \int_0^{\pi/2} \cos\phi\, d\phi \Big/ \int_0^{\pi} d\phi$$

$$= 17.4 \cos\beta \tag{35}$$

The portion of time in sunlight is

$$\tau = 1 - \cos^{-1}\left(\sqrt{1 - K^2}/\cos\beta\right)/\pi \quad \left(0<\beta<\cos^{-1}\sqrt{1 - K^2}\right)$$

$$= 1 - \cos^{-1}(0.312/\cos\beta)/\pi \quad (0<\beta<71.82°)$$

$$= 1 \quad \left(\cos^{-1}\sqrt{1 - K^2}<\beta<\pi/2\right) \text{ or } (71.82°<\beta<90°) \tag{36}$$

Solar heating averaged over the orbit is

$$C_S = \frac{C\tau}{\pi} \int_0^{\pi/2} \sqrt{1 - \sin^2\theta \sin^2\psi}\ d\psi \Big/ \int_0^{\pi/2} d\psi \tag{37}$$

$$= 89.5\ \tau\ E(\sin\theta)$$

where $E(\sin\theta)$ is the complete elliptic integral of the second kind.

A heat balance on the satellite takes the form

$$\sigma T_a^4 = I + (Q + C) \quad \alpha/\epsilon$$
$$= 24.4 + \left[17.4 \cos\beta + 89.5 \text{ E } (\sin \theta) \; (1 - \cos^{-1}(0.312/\cos\beta)/\pi)\right]$$
$$\alpha/\epsilon \qquad (0<\beta< 71.82°) \qquad (38)$$

Using the mathematical expectation of heat fluxes with a random orientation equation (5) becomes

$$\sigma T_a^4 = 24.4 + \left[17.4 \cos\beta + 110.6 \; (1 - \cos^{-1}(0.312/\cos\beta)/\pi)\right] \; \alpha/\epsilon$$
$$(0 <\beta<71.82°) \qquad (39)$$

Equations (38) and (30) are plotted in Figure 11. With random orientation the temperature is observed to be essentially constant for values of between zero and 50°, with much higher temperature for larger values of β. This is due to the decrease in albedo heating offsetting the increase in time spent in sunlight as β increases to a certain value — for β exceeding 82° the satellite is always in the sunlight. For an easterly launch from the United States, β will vary from zero to as much as 55° during a six month lifetime - an α/ϵ ratio of 1.3 appears to be near optimum.

Figure 11 shows the effect of orientation on average temperatures. It is observed that orientation with respect to the sun can make a difference of ±20° F on average temperature. Tumbling in the orbital plane is undesirable since a large β effect on temperature occurs. It would be desirable to keep θ nearly constant.

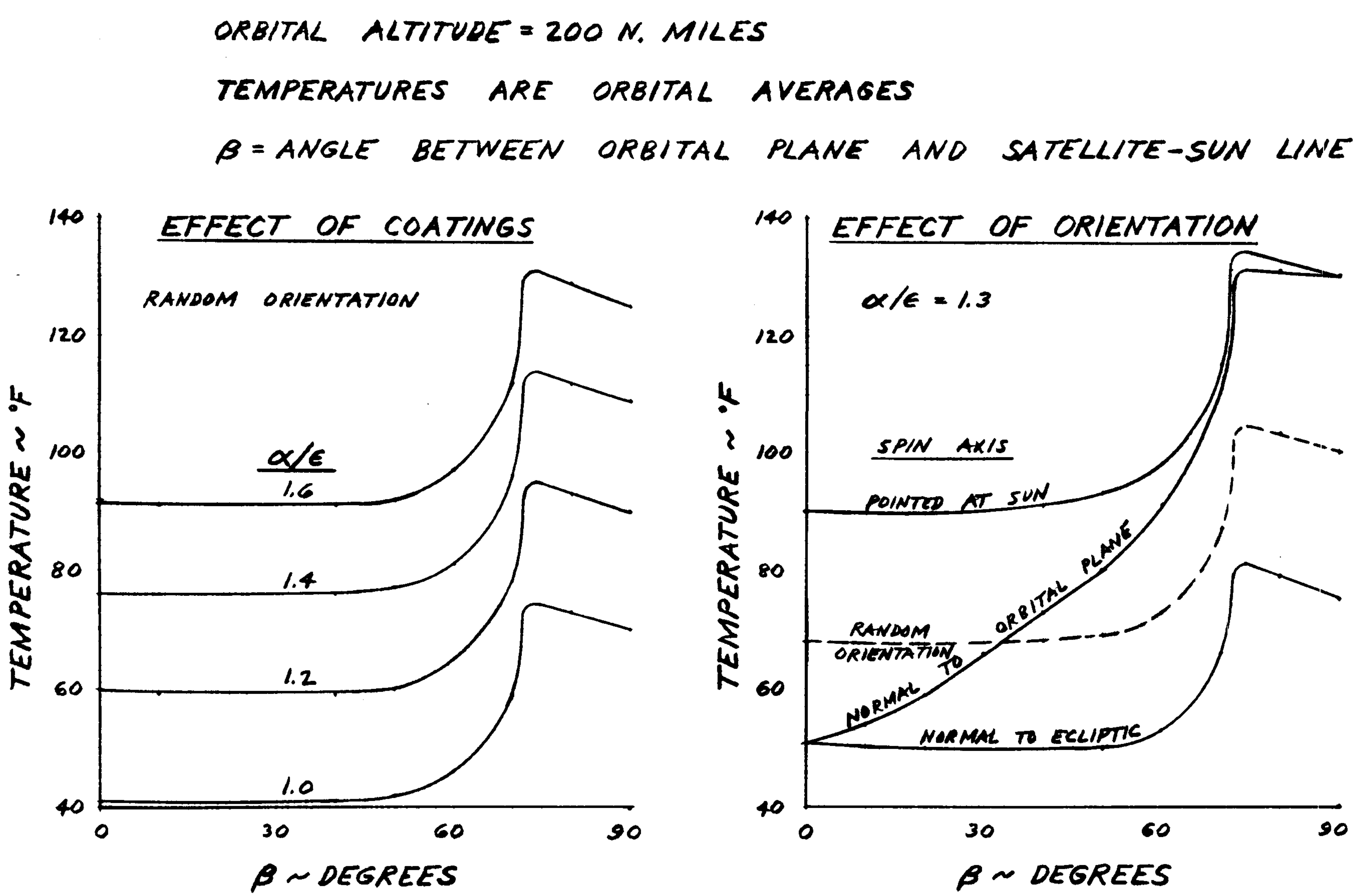


Figure 11. - Temperature of tumbling cylinder.

Canister Design for Prototype Testing

A canister design was prepared to support the prototype test program. This canister will be used during the packaging, packaging load, and deployment tests. The canister to be employed is a cylinder large enough to encompass the 13-foot diameter test article. Its length is approximately 2-1/2 feet. The specific length is to be determined when the prototype model is put into the packaged condition for the first time.

This canister restrains the test unit longitudinally. The cylindrical portion will be restrained by attachment of the cylindrical canister to the tangent rings. In addition, end covers are included in the design, and for a series of packaging load tests these covers will be installed. They will restrain the curved end portions from extending freely.

A mechanism is included which will permit deployment from the canister in the vacuum chamber. This mechanism uses a series of bell-crank type latch fittings which prevent deployment until triggered. At deployment the bell-crank arm's resisting movement swing out of the way to permit unhindered movement of the test article out of the package. The other arms of the bell-cranks are held in position until deployment by a single cable. Deployment is initiated by cutting this restraining cable with a pyrotechnic operated cutter. This arrangement is schematically shown in Figure 12.

The test canister structure is a weldment of aluminum extrusions. A cylindrical sleeve of clear acrylic plastic is inserted into this weldment and bolted in place. This provides a smooth surface for contact with the packaged article before and during deployment tests, while at the same time allowing visual monitoring of the packaged article at all times.

FABRICATION OF PROTOTYPE MODEL

General

The major steps of prototype fabrication include tasks of facility preparation, fabrication aids, hardware fabrication; composite material lamination, tape manufacture, subassembly and assembly of prototype.

The paragraphs that follow describe the major tasks.

Facility Preparation

The initiation of the manufacturing effort involved a limited amount of facility preparation. The task of laminating bladder panel components required

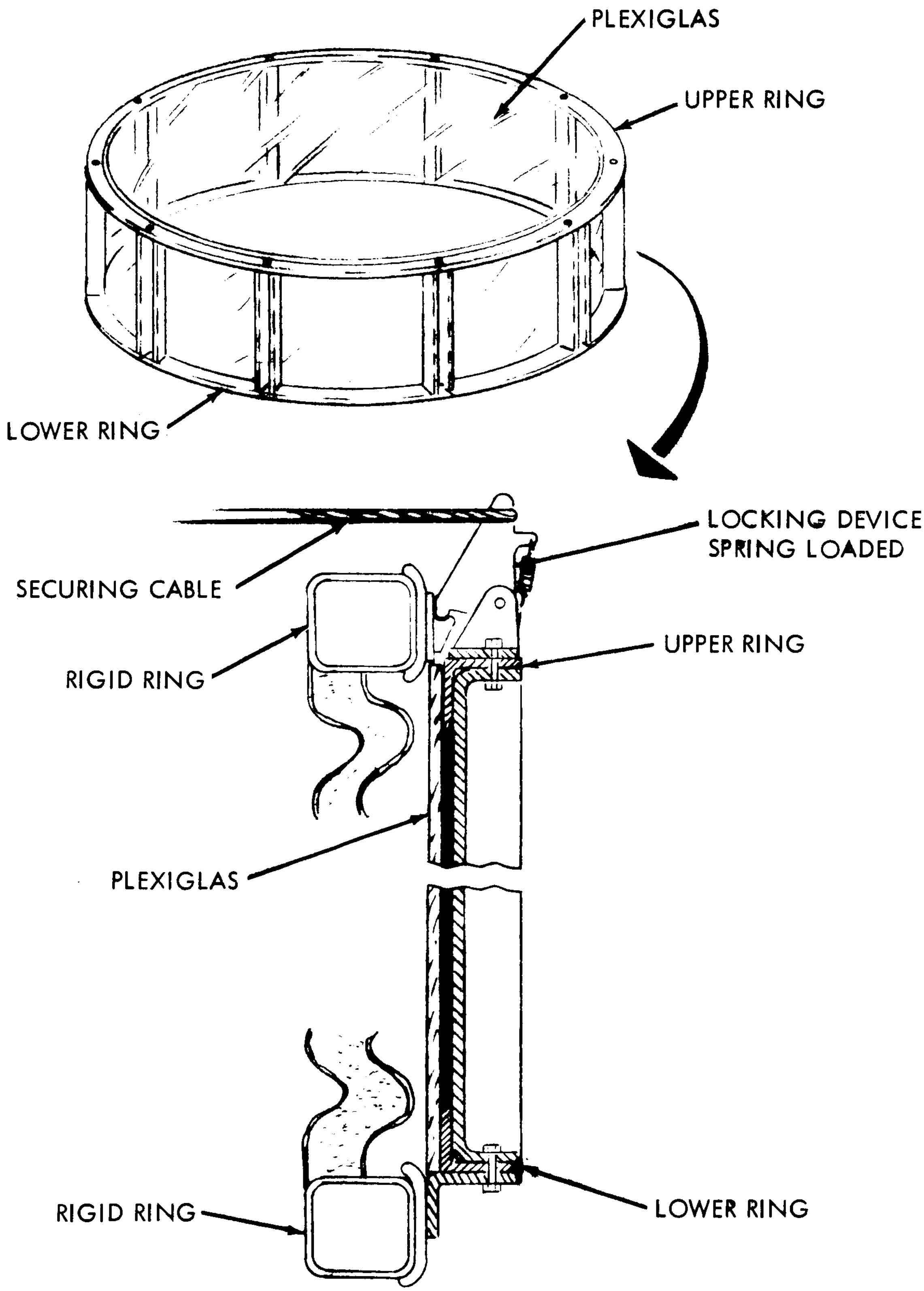


Figure 12. - Prototype test canister.

the adaptation of existing tables for material preparation, and subsequent vacuum bagging. This is the technique used for clamping during adhesive cure.

The Dacron tape was made on a filament winding machine, Figure 13. Two special guides were required to properly orient the yarns which were taken from 28 individual spools, as they passed through a resin bath and onto a windup drum. The guide adjacent to the drum determines the final relative position of the individual yarns, thereby controlling tape width and uniformity. The drum which was available is a sheet metal cylinder, 5 feet in diameter and 12 feet long, but required the addition of a shaft for mounting on the machine. The drum holds approximately 900 feet of tape. Some simple storage spools for finished tape were also made.

The assembly procedure involved a major amount of the effort being accomplished while the structure was flat on the floor (see Figure 14). Therefore, a floor area of 48 x 56 feet was prepared by bonding 1/4-inch masonite to the floor to provide a smooth working surface to prevent damage to the bladder material as it was walked on. Straight cold rolled steel bars were attached to the floor on two sides of this work area to provide permanent reference lines from which to take all measurements during the fabrication phase.

Hardware Fabrication

The hardware items include external and internal tangent rings, packaging rings, bladder terminal rings, doors, and longitudinal strap terminal rings. These items were all produced using conventional metalcraft manufacturing techniques. The access doors were pressure tested to ensure that no leakage would be obtained through welded joints, and that they could adequately resist the pressure loads. Each door was clamped in a manner simulating final installation and pressurized to 16 psig. This setup is shown in Figure 15.

Tape Manufacture and Subassembly

Fifteen rolls of tape were manufactured as shown in Figure 13. The yarn was taken from 28 spools, passed through a polyester resin both with the help of special guides on either side of the bath, and onto the temporary storage drum. This drum had been previously covered with a scrim cloth layer. After curing the resin with infra-red lamps, each full drum (900 lineal feet) was stored on a spool. The scrim cloth was slit during the unwinding of operation, and carried with the yarn until installation onto the bladder.

Approximately 4400 feet of this tape were subassembled to form the longitudinal straps. Since these straps are in effect continuous, passing back and forth from one terminal ring to the other, a number of buckle splices were

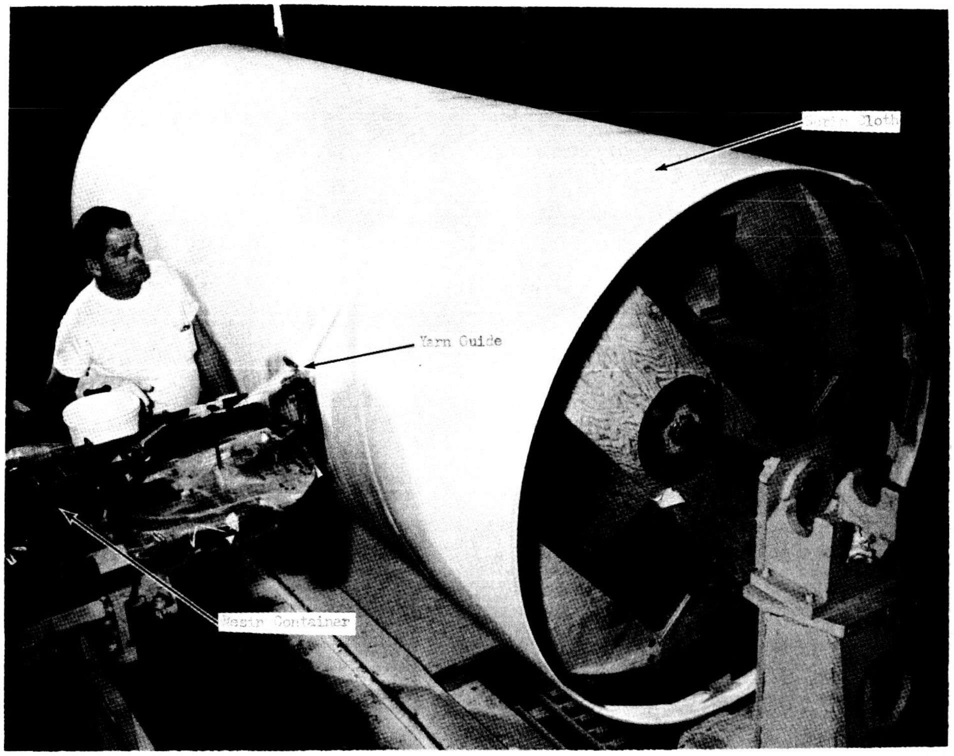


Figure 13. - Tape manufacturing setup.

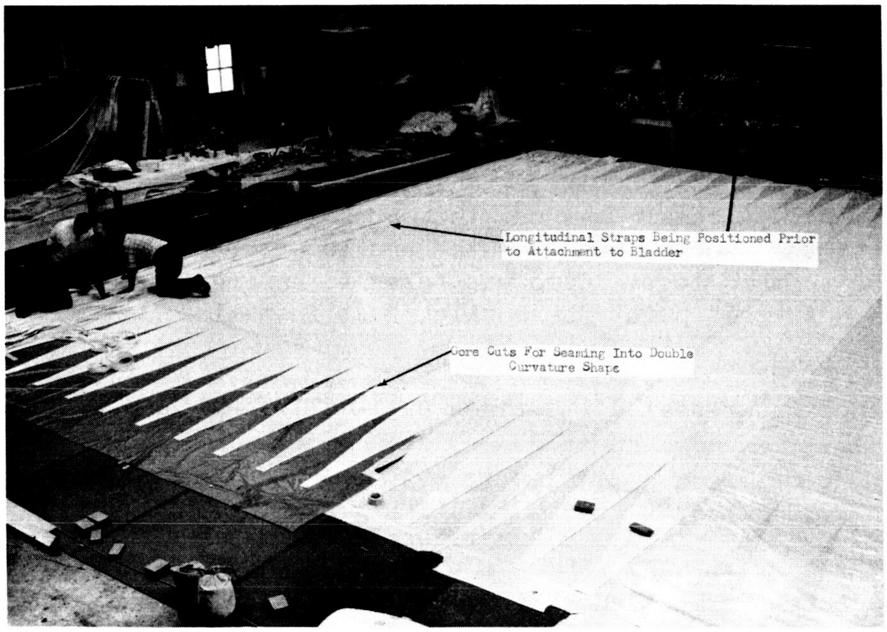


Figure 14. - Prototype bladder assembly.

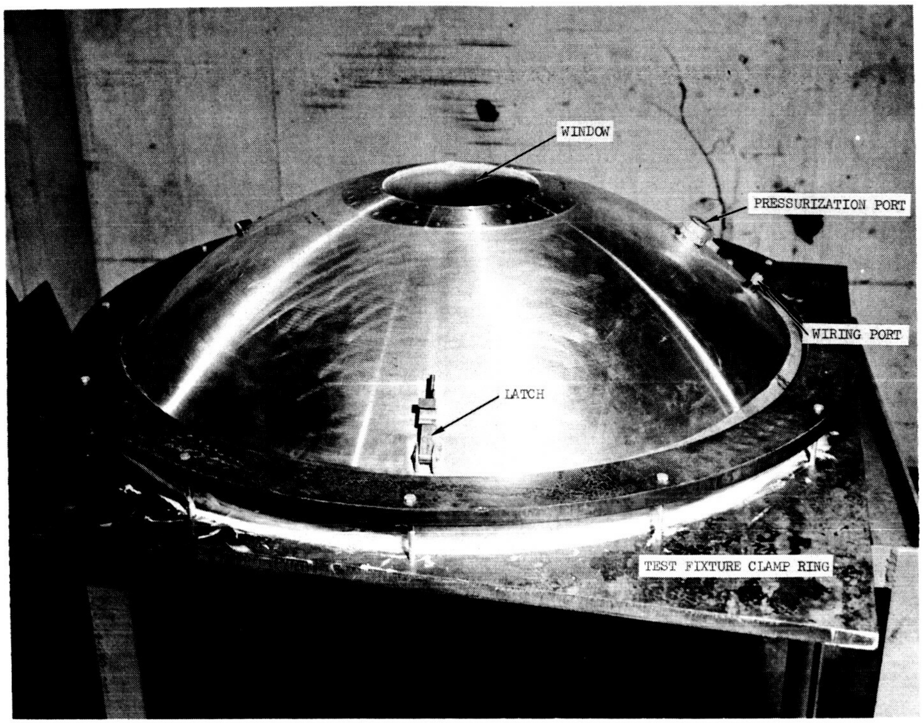


Figure 15. - Access door pressure test setup.

required to join the 900-foot lengths. The longitudinal strap subassembly was completed prior to application to the bladder. Accurate length from terminal ring loop to terminal ring loop was controlled by subassembling over pins mounted in the floor at precise locations. The fabrication sequence was to install the first buckle and bond in place. This was located at the proper distance from the first loop. Next, the rough loop location was established at the opposite end. A buckle was put into approximate location with the doubled-strap through it, the loop placed over the pin locator, and the buckle accurately located relative to this loop. Care was taken to ensure that each strap had uniform tension. At this point the buckle, just installed, was clamped and bonded.

This sequence was repeated 120 times until all longitudinal straps were accurately joined.

Bladder Manufacture

The manufacture of the bladder involved first, the lamination of the bladder material components into a composite material. This was followed by subassembling these panels into the proper flat pattern shape. Next, the longitudinal strap assembly was attached to the bladder and the end gores joined. This was followed by the wrapping of the assembly into a tubular shape and splicing.

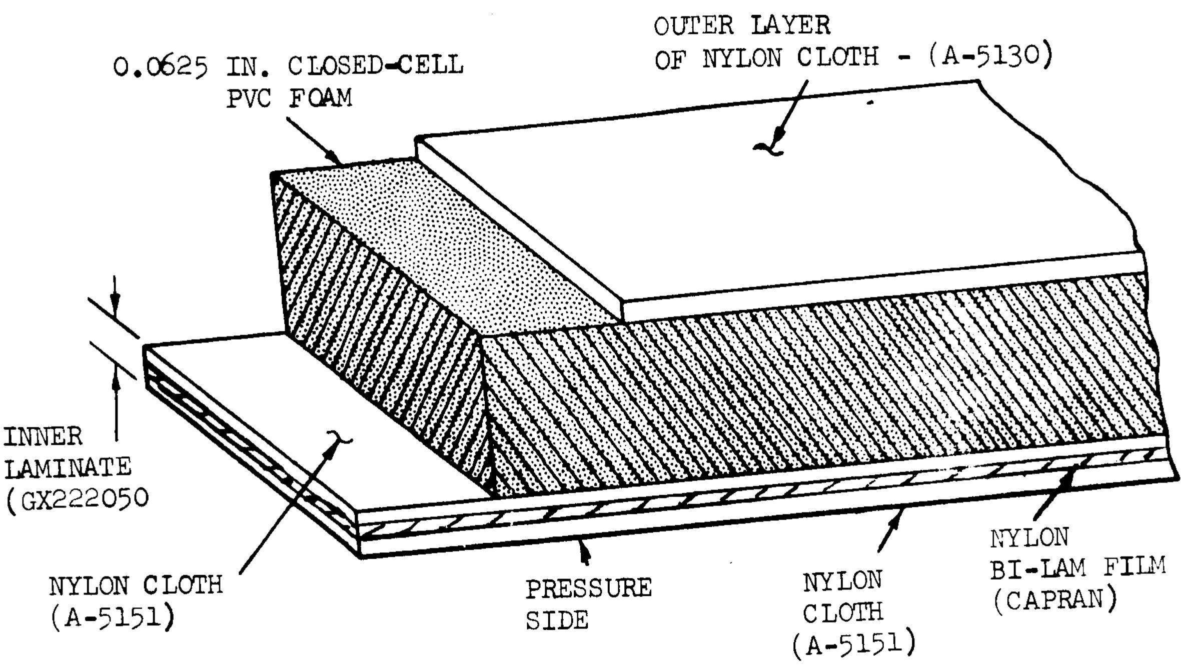
Bladder Material Lamination. - The pressure bladder materials composite is described in the "Materials and Materials Testing" report (Reference 3). The materials available to GAC at the initiation of this program were the cloth-bilaminate film-cloth laminate, the PVC foam, and the outer layer cloth. The first operation at GAC was to laminate these materials into the pressure bladder composite. This composite is shown in Figure 16. Lamination of these components was carried out by first applying the polyester adhesive to both mating surfaces of the layers to be joined. The components were then placed on a scaled table suitable for subsequent oven cure. The composite was then vacuum-bagged to maintain clamping pressure during cure. The entire table was then put into the oven and the adhesive system cured. The locations where the bladder panels were to attach to the tangent rings were determined prior to this layup operation. The PVC foam was omitted locally in these areas. This resulted in the bonding of the film-cloth laminate directly to the outer cloth in these regions. This arrangement provides means of carrying the loads from the internal tangent rings (floor support structure) directly into the longitudinal straps without a soft connection through the foam layer.

Thirty-six composite bladder panels were required to make the entire bladder.

Bladder Subassembly. - Bladder panels were joined into a flat pattern on the floor area which had been specially prepared. The rectangular panels were accurately trimmed to pre-determined sizes. They were laid on the floor with the film-cloth side down, and 2-inch wide film-cloth tape applied using polyester room temperature adhesive.

The assembly was then inverted. Film-cloth tape was applied to the film-cloth side in the same manner. However, immediately prior to putting the tape in place a 1/8-inch diameter bead of RTV Silicone was injected into the joint. The pressure of applying the tape caused the silicone to flow out over the film cloth approximately 1/4 to 3/8 inch on each side. This bonded well to the film-cloth of the panels and to the tape, resulting in an excellent seal.

It was necessary to remove excess material from the ends of this flat pattern to provide gores which could be seamed together to form the proper end contour. This is shown in Figure 17. The proper gore shape was derived from a plaster model of the end. See Figure 18. These gores were joined and taped in the same manner as other bladder joints. See Figures 19 and 20. Several of these gores were left unjoined while the bladder was on the floor. This permitted sufficient access to the inside to later install large hardware items such as packaging rings.



ITEM	WEIGHT (PSF)
INNER LAMINATE (GX222050)	0.034
POLYESTER ADHESIVE (VITEL)	0.010
CLOSED-CELL PVC FOAM	0.042
POLYESTER ADHESIVE (VITEL)	0.010
OUTER NYLON CLOTH (A-5130)	0.012
TOTAL	0.108

Figure 16. - Pressure bladder.

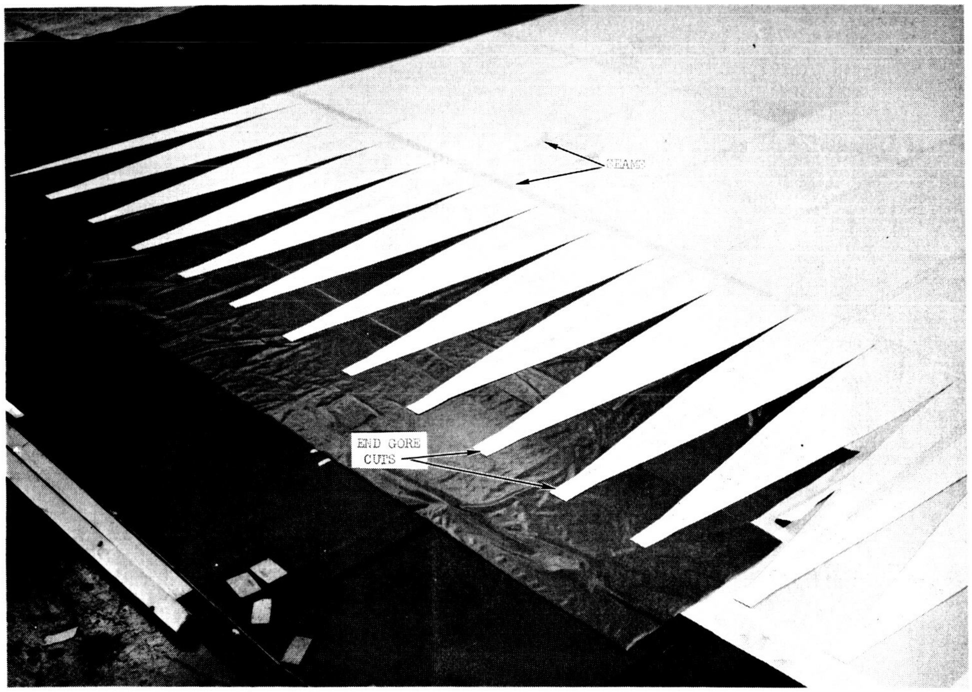


Figure 17. - Subassembly.

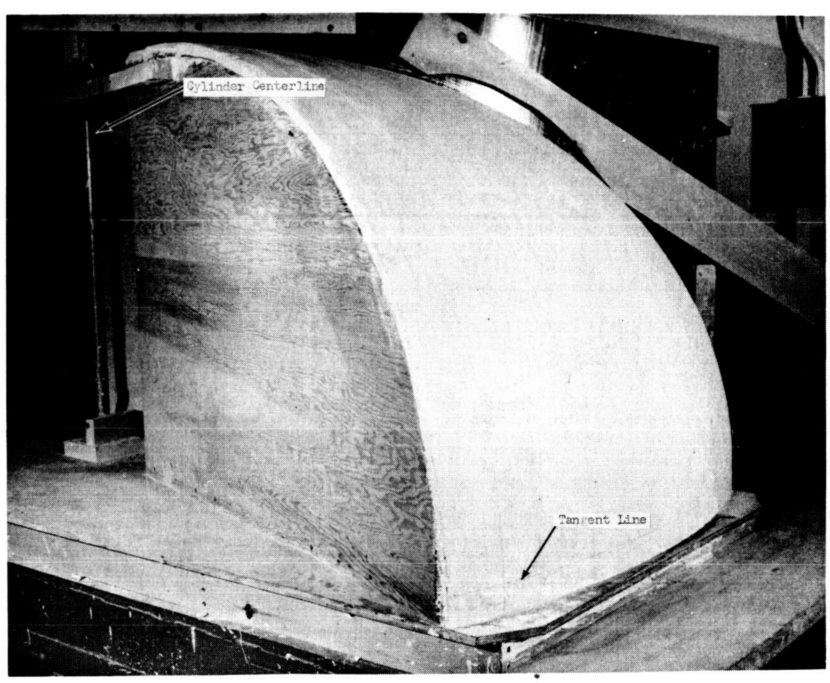


Figure 18. - Contour model for bladder development.

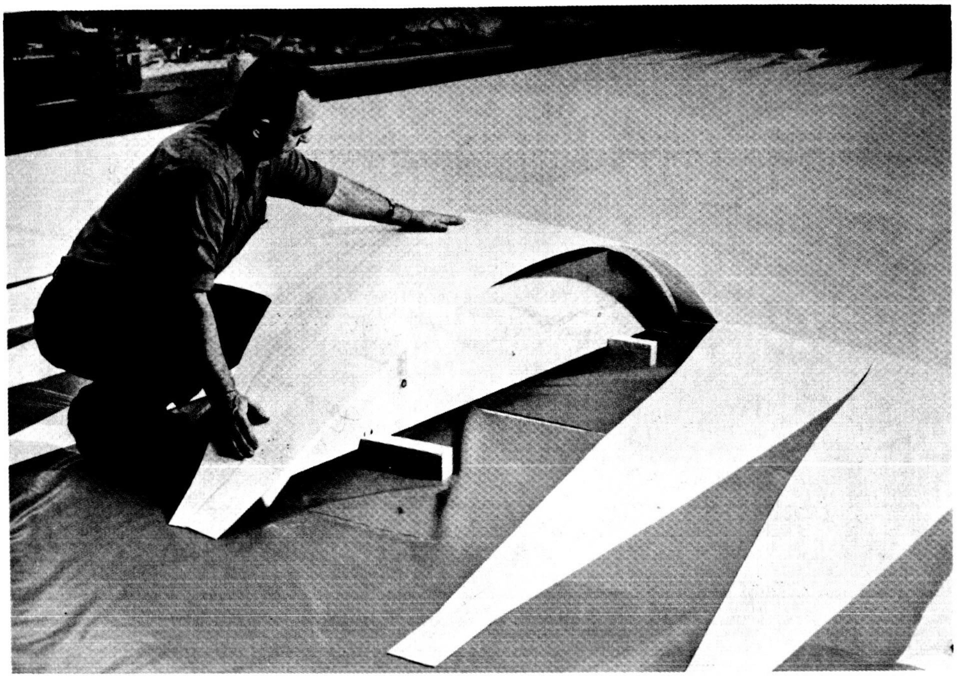


Figure 19. - End gore seaming.

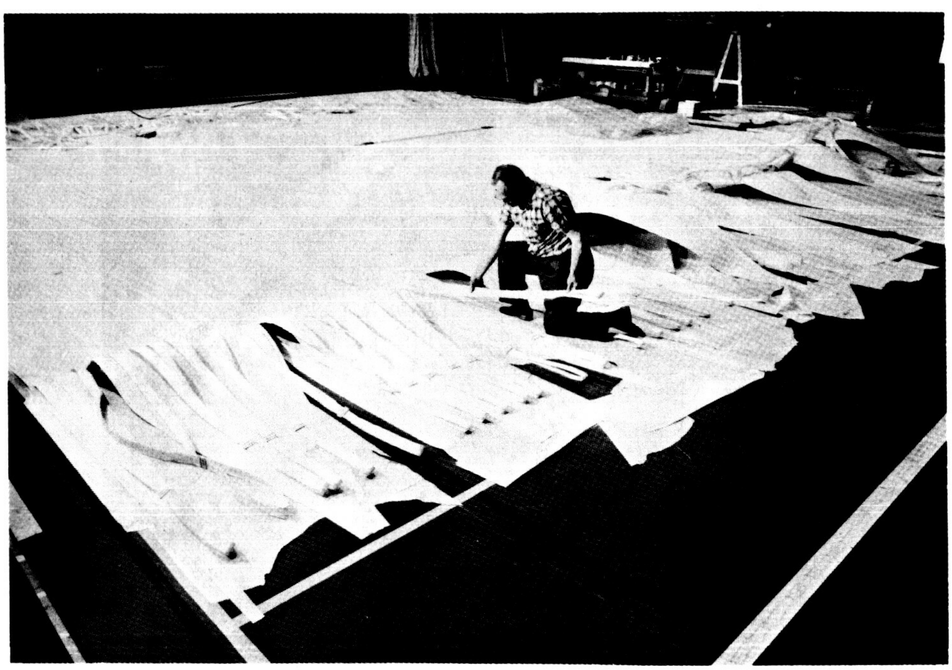


Figure 20. - Bladder assembly.

Installation of Longitudinal Strap Assembly. - The last step in the bladder assembly was that of attaching the longitudinal straps. This operation is shown in Figure 20. The strap locations were marked on the outside of the bladder while on the floor. Attachment was then made between tangent points of each strap. Tangent point locations previously marked on the straps were coordinated with the tangent lines on the bladder. The straps were weighted for clamping pressure during initial cure of the RTV silicone adhesive used. Figure 21 shows a typical area where straps are attached to bladder. A longitudinal splice is also shown in this picture. The short straps were then bonded in place for attachment of the external tangent rings.

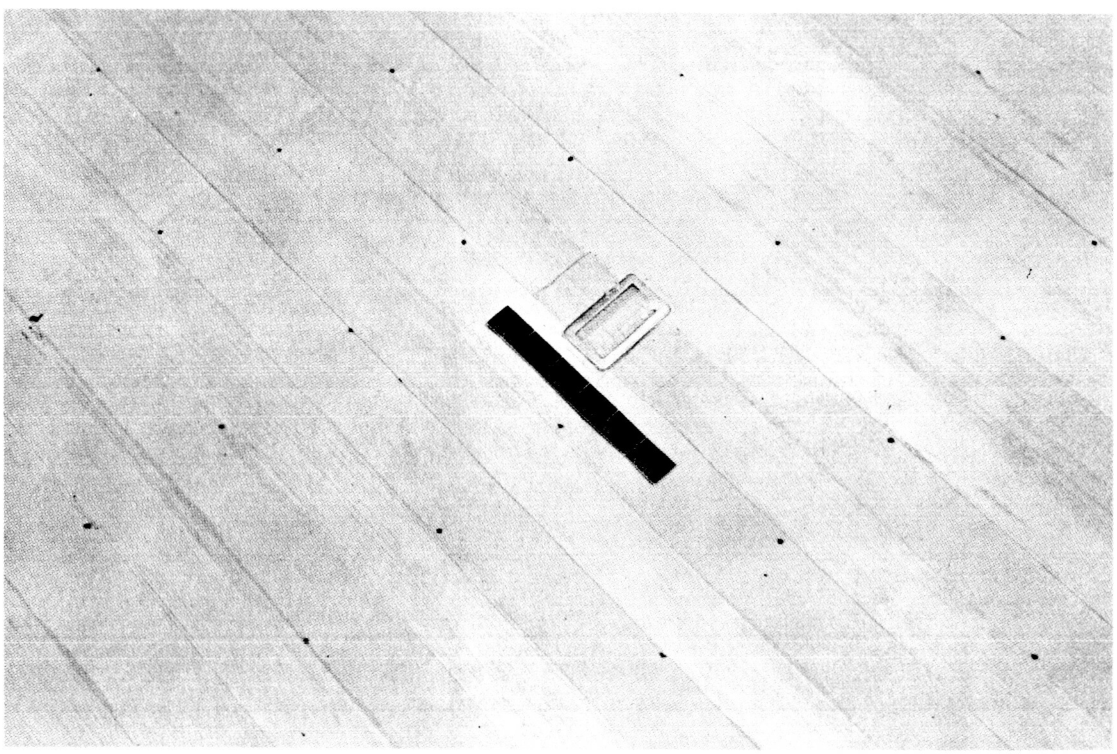


Figure 21. - Longitudinal tape attachment to bladder.

Final Bladder Longitudinal Seam. - The bladder edges were finally brought together and the last seam made to make a tubular structure. After the bladder joint was completed, the first and last straps were joined using match marks put on during strap subassembly for coordination. (The bladder assembly was then complete with the exception of the final gore seams in each end, and the attachment of the straps to the bladder in the curved end regions. In this condition the bladder was hoisted into a vertical position for hardware installation. This is shown in Figure 22.

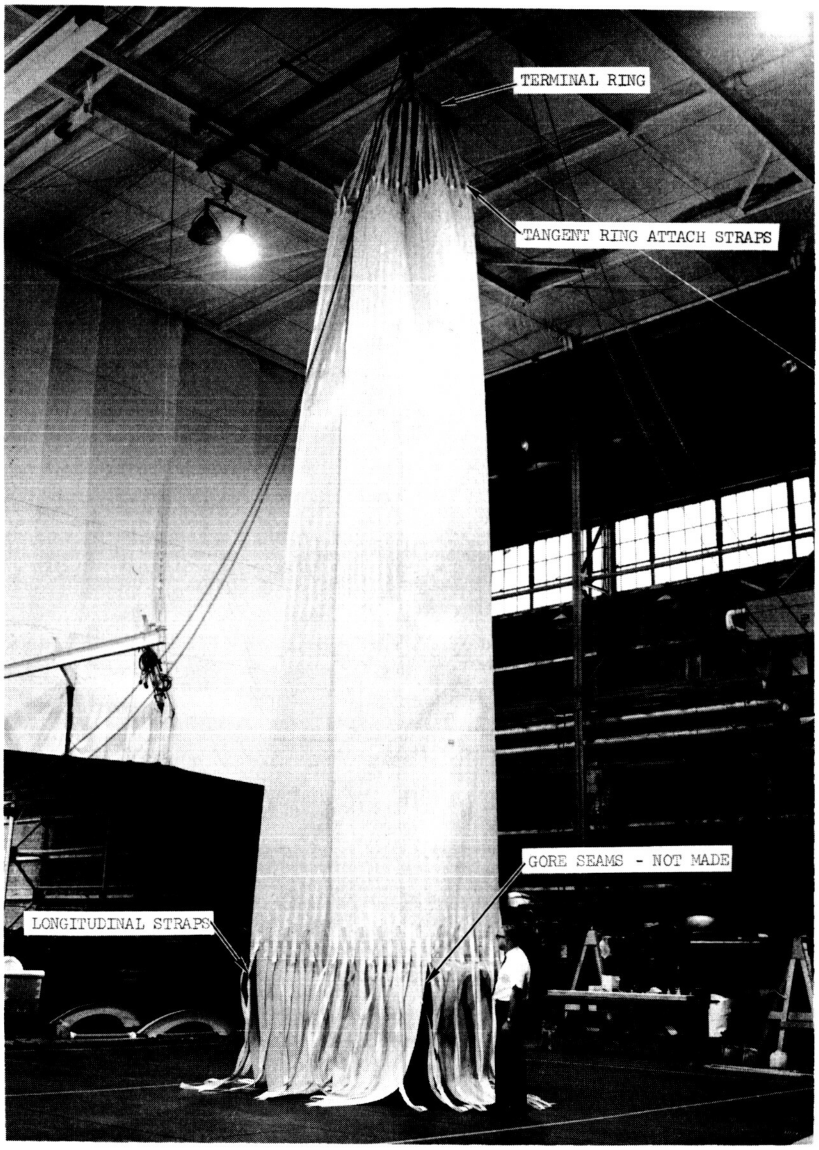


Figure 22. - Prototype model ready for hard structure.

Hardware Installation

Packaging Ring. - The first hard-structure component to be installed was a packaging ring. The foam to which the packaging ring was attached was first bonded in place using polyester adhesive. Locations were derived from earlier layout while the bladder was flat on the floor.

The tie-strap assemblies were then bonded in place and the first packaging ring inserted through the end. After location, the straps were tied and bonded to the ring.

The packaging rings can be seen in place in Figure 23. In this view temporary spokes can be seen in these rings to ensure that they are not damaged in subsequent fabrication operations. These are to be removed prior to packaging.

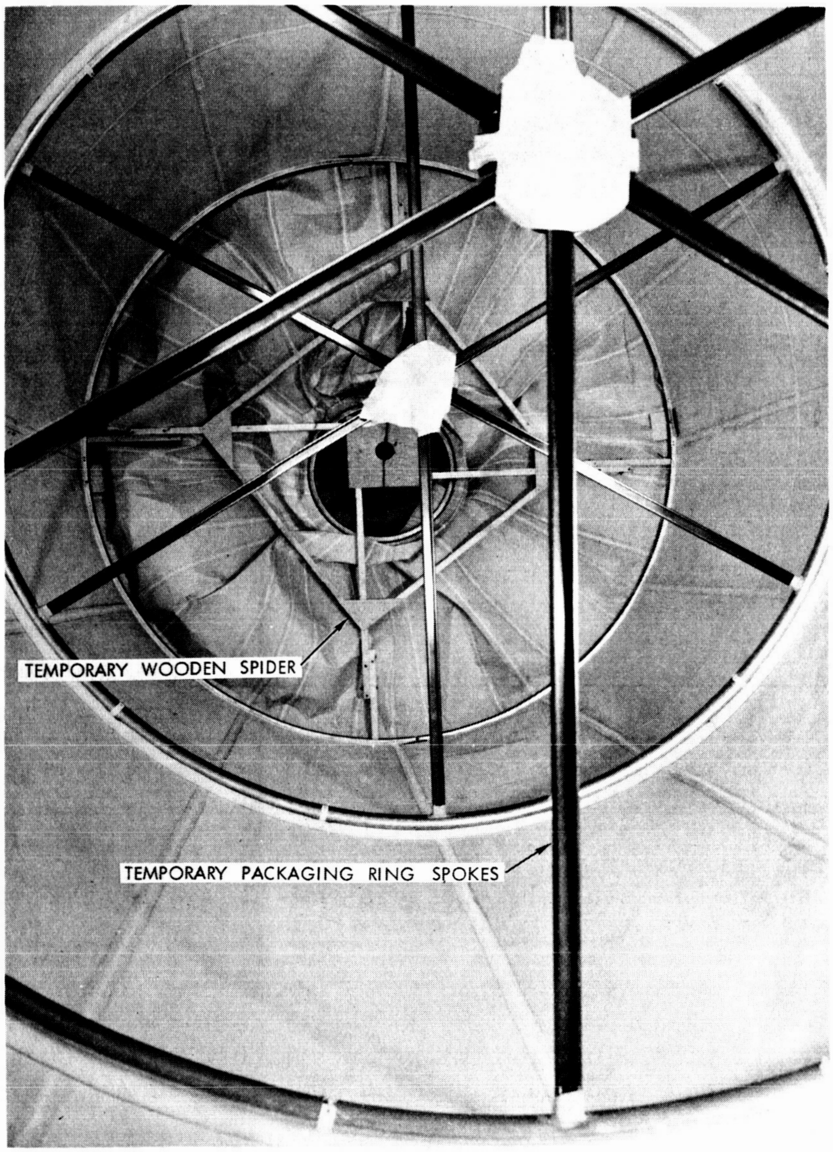


Figure 23. - Prototype model inside view showing internal hardware.

Tangent Rings. - The external tangent ring was then installed at the lower end. Attach straps were already in place. These straps were folded over the ring and clamped in position during cure with clamp plates and C-clamps. Epoxy adhesive was used for this attachment.

The lower internal tangent ring was then inserted. This ring was made in four pieces with turnbuckles at the joints to provide adjustment for a tight fit against the inside of the bladder. This also provided clamping pressure during cure of the adhesive. RTV silicone was used for this attachment.

Temporary Spider. - A temporary wooden spider was then inserted into the internal tangent ring. This can be seen at the far end in Figure 23. This is a fabrication aid to be removed later. The hole in the center is for insertion of a stub shaft to be used during the circumferential tape wrapping operation. The design of this spider allowed adjustment of the arms to obtain a tight fit into the internal tangent ring and also accurately locate the shaft hole on center.

The finished door to be installed at this end was then temporarily attached to the spider. This was simply to stow the door which could not be inserted after the bladder terminal rings were in place.

Terminal Rings. - The next step in fabrication was the installation of the bladder terminal rings. First the remaining gore seams at this end were completed. The hole was trimmed in the bladder to the appropriate size to match the bladder terminal rings. These rings were then bonded in place, again using RTV silicone for adhesion and sealing purposes. The strap terminal ring halves were then inserted through the strap loops and joined. Figure 24 shows the prototype model in this stage of completion.

Temporary Door, Stub Shaft, and Handling Fixture. - The temporary door and stub shaft were then installed. The inside door half was split for insertion through the door opening, The stub shaft was inserted through the opening and secured in place in the spider. The split inside-door half was then put together and attached to the outer door half, with the temporary seal in place.

The handling fixture ring, and three supporting arms were then joined to the tangent ring and the stub shaft extension. This arrangement can be seen in Figures 25 and 26.

The prototype test unit was then inverted and the same procedure followed for installation of hardware and temporary fabrication aids on the other end. Figure 25 shows the model in the inverted position with the second tangent ring installed, and this end ready for the stub shaft, temporary door, and handling fixture installation.

Circumferential Tape Wrap. - The test article was then placed in a horizontal position and the stub shafts placed in trunnion stands. This position is

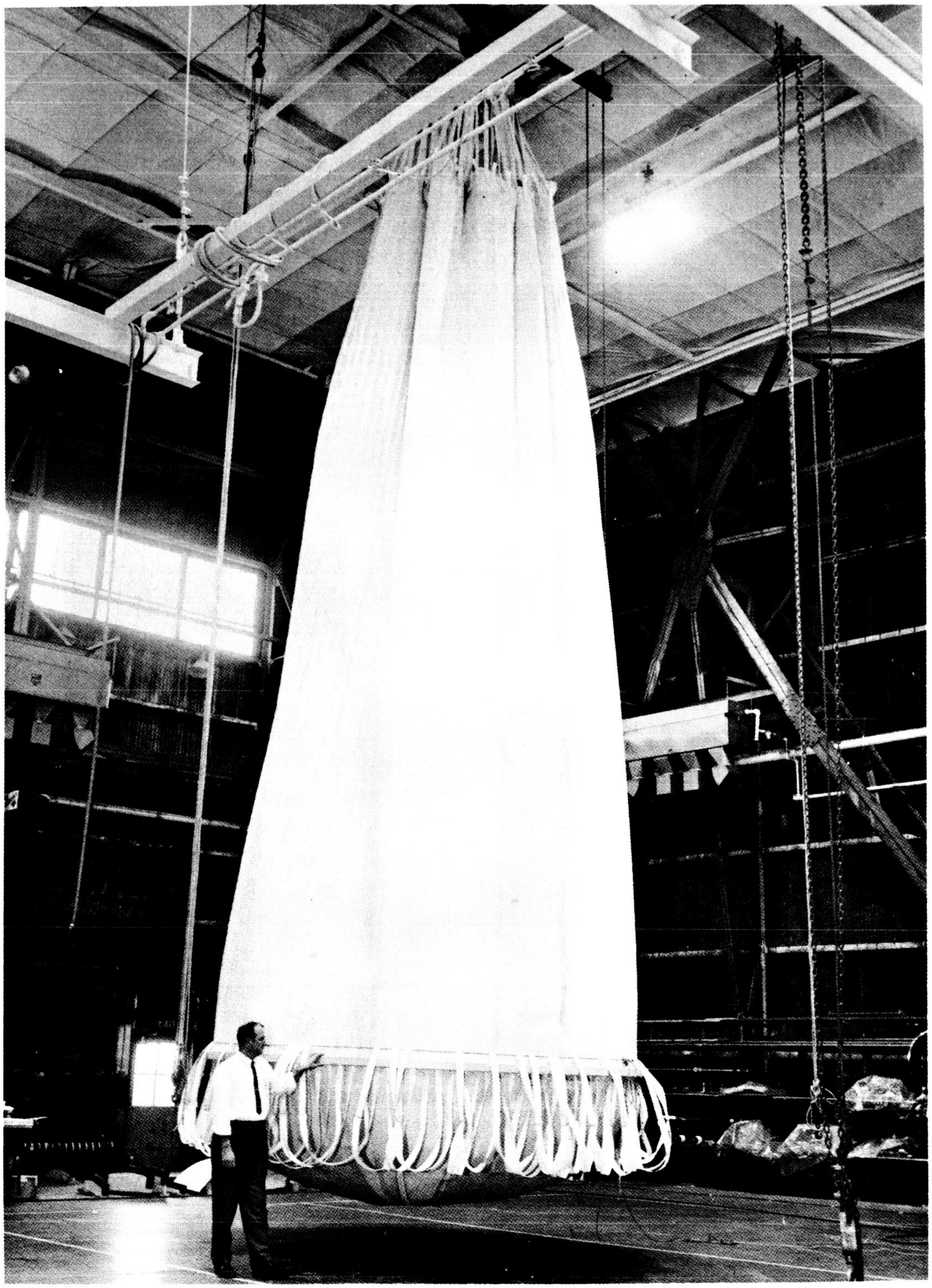


Figure 24. - Prototype model with hardware installed at one end.

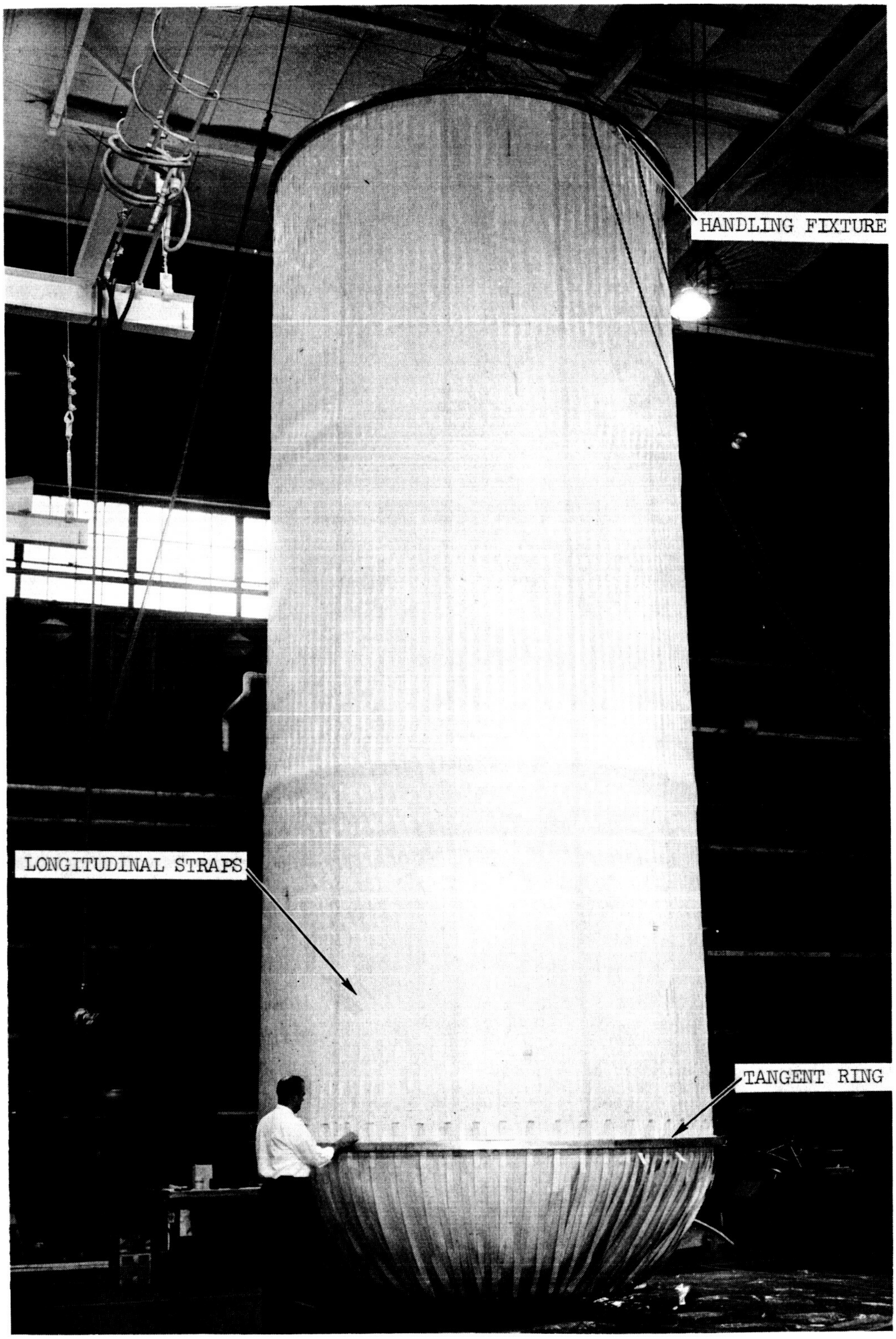


Figure 25. - Prototype model with hardware installed.

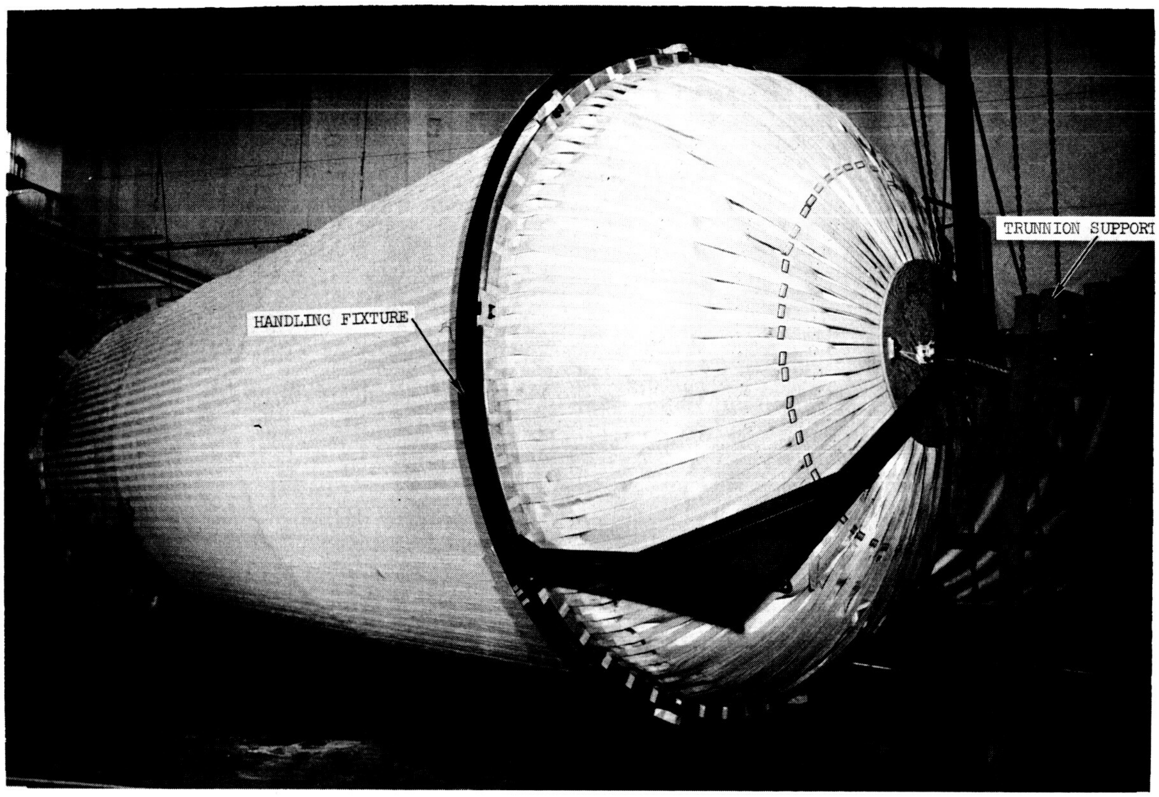


Figure 26. - Prototype model in horizontal position.

depicted in Figures 26 and 27. The trunnion stands provided cantilever support for the stub shaft. In this manner the weight of the test article from the tangent rings outward was supported by the trunnions. This left only the weight of the flexible structure between tangent rings, and the two packaging rings to be supported (see Figure 28). The unit was then pressurized to approximately 2 inches of water. This air pressure was introduced through one of the shafts (see Figure 27). It was then stiff enough to permit removal of the handling rings and arms.

Supporting rubber-tired idler wheels were then installed to act as steady rests for turning the model during tape wrapping. This setup is shown in Figure 29. Four wheels were used on each side. Two were placed under the tangent rings, and two under the packaging rings. The wheels on one side under the tangent rings were interconnected with a common shaft. These wheels were driven by a friction pulley mounted on a variable speed drive unit. Thus, no twisting of one end relative to the other could occur during the wrapping operation.

A crude tape wrapping device was constructed, shown in Figure 29. The Dacron tape spool was mounted on the movable holder. A friction device restricted the

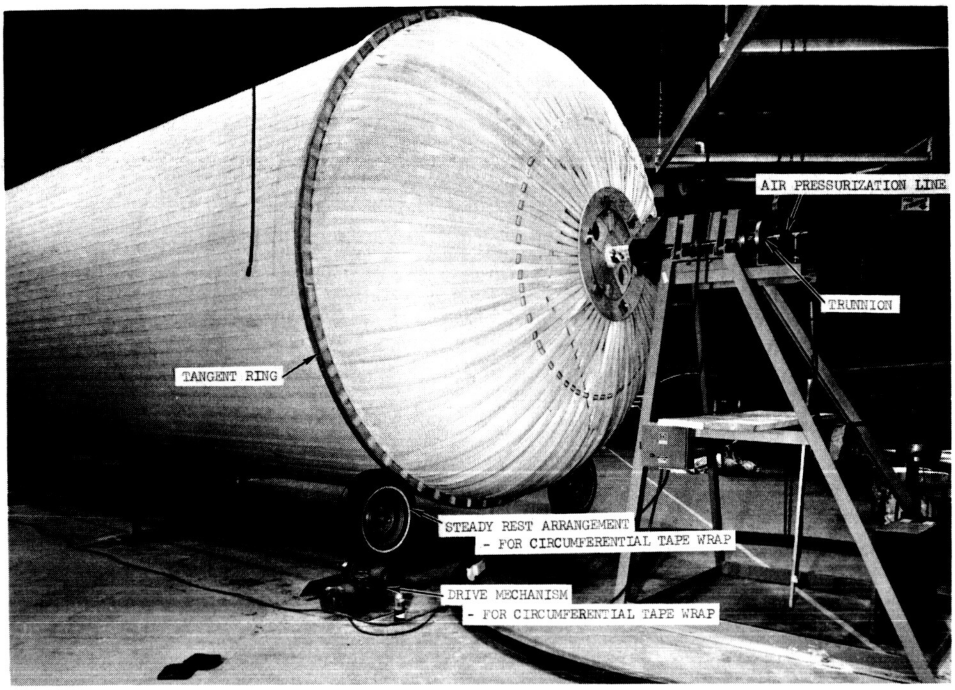


Figure 27. - Trunnion support and drive mechanism.

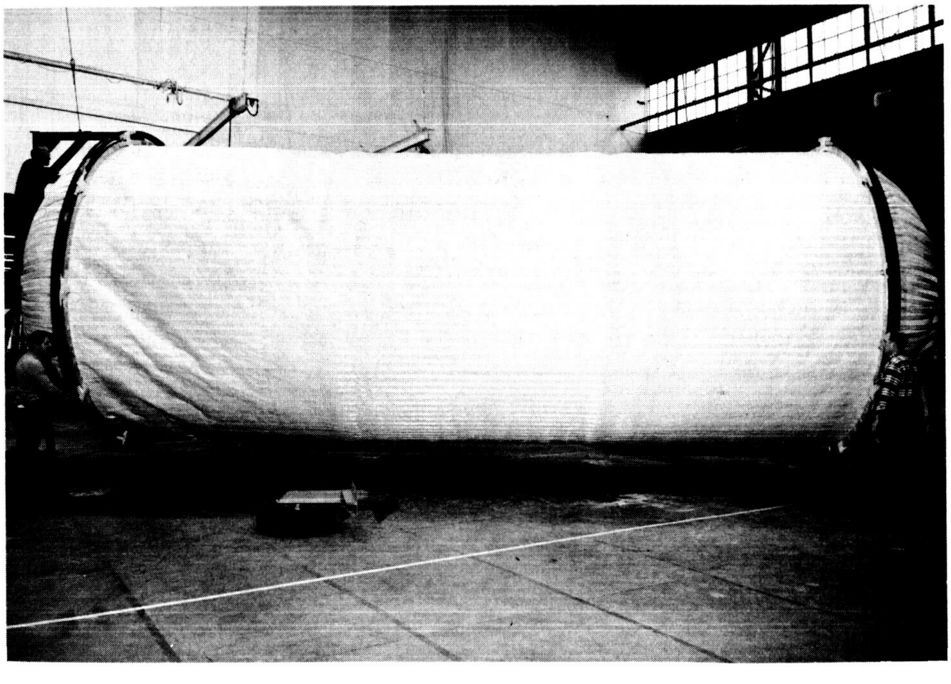


Figure 28. - Prototype model supported by trunnions and stub shafts.

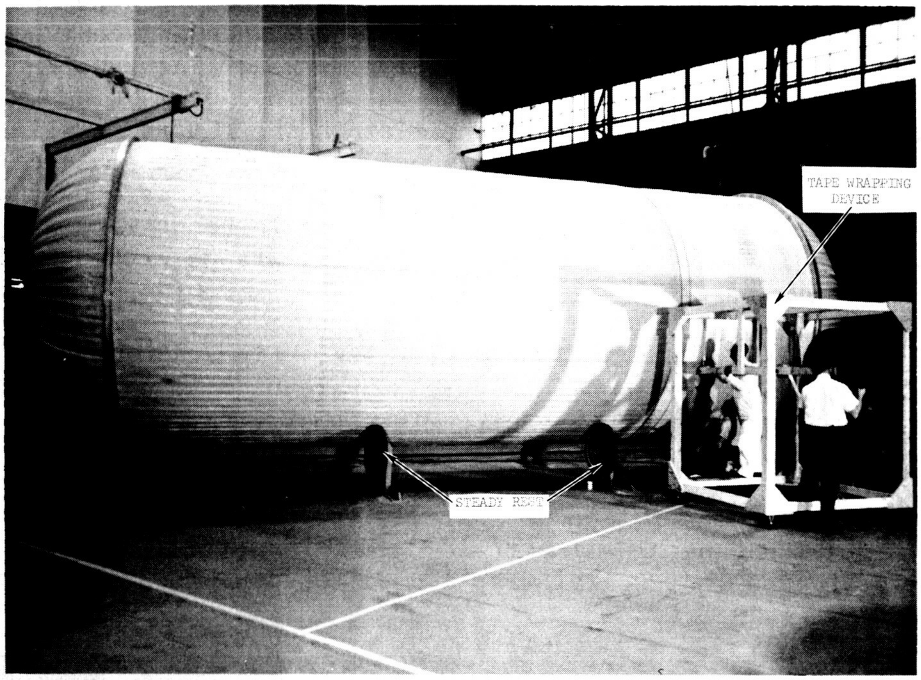
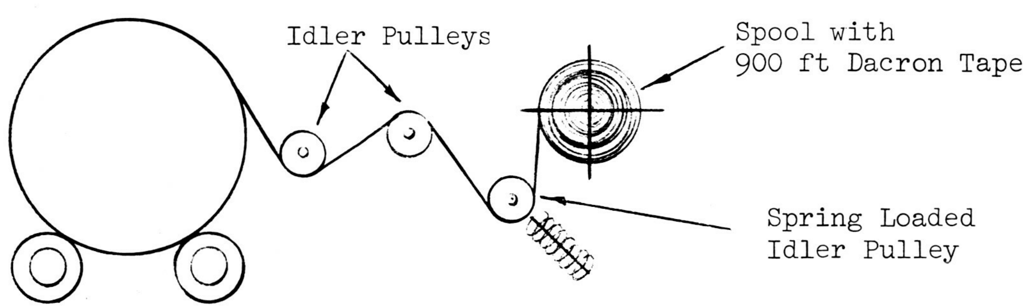


Figure 29. - Prototype model - circumferential tape installation.

rotation of this spool. The tape passed through a team of idler pulleys to the model. This is schematically schematically shown in the following sketch. Uniform tension was maintained on the tape by a spring-loaded idler pulley.



RTV Silicone was used as the bonding agent to attach the tape to the bladder. This material was introduced immediately ahead of the tape as it was wrapped onto the model. One complete wrap was made adjacent to one tangent ring. From that point a spiral was followed. The tape progressed 2 inches per revolution. The spiral path was defined by markings which had been put on while the bladder was in the flat on the floor. A slight dilation of the structure resulting from the internal pressure of the bladder was apparent prior to wrapping. For this reason steel bands were used to cinch the structure into the correct circumference. These bands were slipped along the structure immediately ahead of the area being wrapped to maintain uniform circumference.

Figure 29 shows this operation in progress. Figure 30 shows the operation complete. The steel bands seen in Figure 30 were used to maintain clamping pressure over buckle joints in the circumferential tapes while the joint adhesive was curing. These bands were later removed.

The last revolution of tape was parallel to the tangent ring. The tape was terminated using a buckle like those used for splices. This buckle ties the outer wrap to the last spiral wrap immediately underneath.

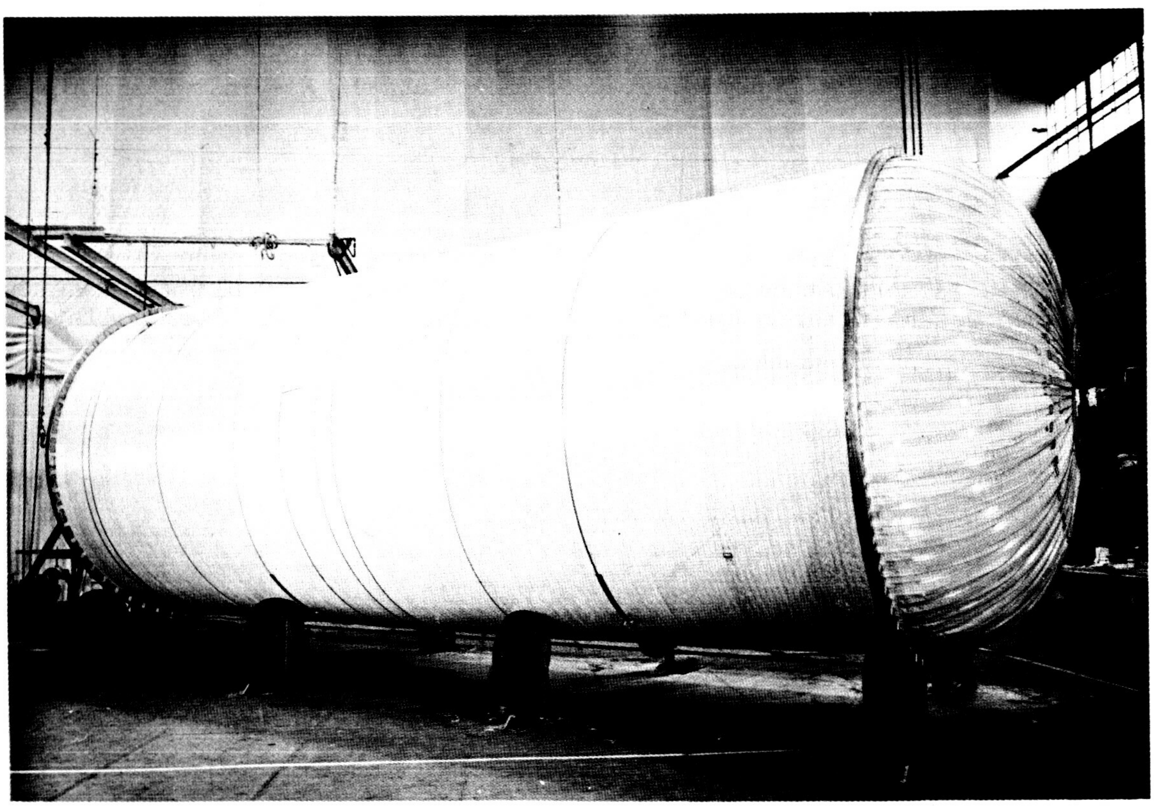


Figure 30. - Prototype model - circumferential tape wrapping complete.

Finish Door Installation. - When tape wrapping was complete and adequate cure time was achieved, the unit was placed in a vertical position and the temporary door and stub shaft removed from the lower end. The matching door seals were mounted on the door and door frame, and the door installed. The unit was then inverted and the same operation completed on the opposite end.

This was followed by the preliminary leak test described later in this report.

Attachment of Longitudinal Straps. - The next task was the attachment of the longitudinal strap to the bladder in the end regions.

This was accomplished using RTV Silicone as the bonding agent. It was accomplished with a low pressure (2 inches of water) in the model.

This was accomplished with careful attention to uniform orientation of the straps where they attach to the bladder.

Micrometeoroid Foam Installation. - Bleeder provisions were made on the outer surface of the structural tape to aid in evacuation of the structure wall for packaging. First a network of polyethylene spiral-wrap tubing was installed by taping to the outer surface. In addition, triangular cross-section rings of extremely open-cell foam were attached to each side of the tangency rings. Thus, openings are assured throughout the wall layer to aid in evacuation of the wall to the tangent rings, when used as manifolds.

The entire structure from doors to tangency rings, and between tangency rings was then covered with 1-3/4 inch thick 1.2 lb/cu ft flexible open-cell foam. This is the micrometeoroid protective layer. This material was applied in slabs. Attachment was made with polyester adhesive. This adhesive was also applied to the edges of the individual slabs so that no void areas would be obtained.

Outer Cover Installation. - The nylon film-cloth outer cover was next applied. This layer provides the seal to permit evaluation of the wall for packaging. It is this surface to which the thermal coating is applied, and acts as the bumper to break up micrometeoroid particles. Rectangular panels were pre-joined on the floor to cover the cylindrical section. These were then bonded in place, again using polyester adhesive. The ends were also covered with the same material. Gored sections were used to follow the curved shape, in the same manner as the bladder was tailored. A complete bond was made also at the ends where the outer cover attaches to the door frame, and at the tangent rings.

PRELIMINARY LEAK TEST

A preliminary leak test was conducted on the prototype model prior to application of the foam and outer cover. The test was conducted at this stage of completion to permit easier location and repair of leaks in the bladder, if necessary.

The design requirements of this structure are specified as follows:

(1) Maximum gas leakage at operating pressure of 2 percent of total internal gas volume per 24-hour period.

(2) The operating pressure is 5 psia in a vacuum environment.

The preliminary leak test requirement specified that the expandable structure shall be inflated to an internal pressure of 1 psi and this pressure maintained for a 24-hour period to determine leak-rate characteristics.

An analysis was made to establish the permissible leak rate under the preliminary test conditions that would be comparable to the specified design requirements under the operating conditions. This is summarized as follows:

Comparing leakage to flow through an orifice with 2 percent leakage in 24 hours at 5 psia permitted, the orifice area is 0.00025 in^2 for a volume of 4350 cu ft.

If the leakage test were conducted at 5 psig on the ground, the allowable pressure decay in 24 hours would be 7.6 in. H_2O. At 1 psig (ground) the allowable decay is 3.0 in. H_2O. This is the target value on which to compare the preliminary leak test results.

The test was conducted with the model in the horizontal position. Three thermocouples were mounted inside, near the centerline, with one near each end and one in the center. A differential water manometer was used to measure differential pressure. Barometric readings were obtained at the start and then at the end of the test.

The initial and final temperature and pressure measurements are listed in Table [illegible].

TABLE [illegible]I. PRELIMINARY LEAK TEST DATA

Date	Time	Barometric Pressure in. Hg	Internal Temperature °F Thermocouple 1	2	3	ΔP in H_2O
3-2-67	8:30 a.m.	28.74	75	75	75	26.90
3-3-67	9:30 a.m.	28.78	75	75	75	24.60

Since the internal temperature was the same at the beginning and at the end of test period, no temperature correction was necessary.

The barometric pressure increased from 28.74 to 28.78 in. Hg. Correcting for this difference the final ΔP at the end of 25 hours was 24.80 in. H_2O. The net loss then was 2.1 in. H_2O. This was well within the 3.0 in. H_2O loss permissible.

TEST PROGRAM DEFINITION

As part of this contract GAC prepared a "Proposed Test Program" report (Reference 6).

This program covers the following tests, to be carried out on the prototype model now complete.

<u>Atmospheric Ambient Testing</u>

Folding and Packaging
Gas Leak Rate
Proof Pressure

<u>Vacuum Chamber Testing</u>

Packaging Load
Deployment
Gas Leak Rate

Since the preparation of the test program report, considerable thought has been given to the testing program. It is recommended that an ultimate pressure test also be carried out at the conclusion of the other tests. This would best confirm the capability of this structure to carry out the functions structurally that have been predicted analytically and by small scale testing of material samples.

CONCLUSIONS AND RECOMMENDATIONS

The program herein reported is the initial phase of an over-all program entitled "A Feasibility Investigation of Expandable Structures Module for Orbital Experiment - Artificial G".

This program included initially a design and analysis task of a full-scale structure. The results were entirely compatible with the basic structure concept on which the design was based. This included test evaluation of materials and material composites subsequently utilized in the design. Concurrently with this task a prototype model was designed, followed by the manufacturing of this unit. The conceptual design included utilization of fabrication techniques which are not conventional. This was necessary due to the extreme size of the product. The goal was to achieve characteristics normally common to filament wound structures, but to do so without the aid of filament winding equipment of a size to handle the complete article.

The results were quite satisfactory, and confirms that considerably larger products can be manufactured using the same basic techniques.

The assembly processes could also be applied using other materials for the structural elements. For example, stainless steel tape instead of Dacron tape could be readily considered. Its use would represent a penalty in weight, but the resulting structure would withstand the pressure loads equally well, with less inflation elongation due the higher modulus of elasticity. Initial tape manufacturing tasks would be somewhat slower since existing equipment used for making the tape would require some modification.

It is recommended that the test program phase be initiated as soon as possible to complete the feasibility investigation herein started. This program should cover the essentials defined by the test program developed under this contract.

It is recommended that one significant design change be made on future structures of this type. The longitudinal tapes should be 1/2 the weight of the circumferential tapes while maintaining the same width. They would then be applied side by side, with essentially no gap. This would provide complete backup for the bladder in the end regions. This is not essential, but does provide protection for the bladder at the relatively small penalty of additional adhesive weight for bonding the longitudinal straps to the bladder.

It is also recommended that additional material optimization work be implemented. This work should be directed towards an overall investigation of the flammability characteristics of the total composite material. Criteria for optimization should include both the end item application and the NASA requirements for crew bay materials currently being reviewed and revised.